



# Post Test Evaluation of HSCT Nozzle Acoustic Liner Subcomponents Subjected to a Hot Acoustic Durability Test

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## **Acknowledgments**

The work described in this report is the result of the collaboration of many individuals, including: Joe Grady, and Kang Lee of NASA Glenn Research Center (GRC); Bob Warburton, Beth Bates, Bob Miller, Dave Machen, and Ramon Mayor of Pratt & Whitney Aircraft Engines; Arnel Patia, Ron Crumbacher, and Ken Wentz of Wright Patterson Air Force Base.

## **Document History**

This research was originally published internally as HSR075 in June 2000.

*Level of Review:* This material has been technically reviewed by technical management.

Available from

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## ABSTRACT

The acoustic liner system designed for use in the High Speed Civil Transport (HSCT) was tested in a thermal-acoustic environment. Five ceramic matrix composite (CMC) acoustic tile configurations, five bulk acoustic absorbers, and one thermal protection system design were tested.

The CMC acoustic tiles were subjected to two 2 ¾ hour ambient temperature acoustic exposures to measure their dynamic response. One exposure was conducted on the tiles alone and the second exposure included the tiles and the T-foam bulk absorber. The measured tile RMS strains were small. With or without the T-foam absorber, the dynamic strains were below strain levels that would cause damage during fatigue loading.

After the ambient exposure, a 75-hour durability test of the entire acoustic liner system was conducted using a thermal-acoustic cycle that approximated the anticipated service cycle. Acoustic loads up to 139 dB/Hz and temperatures up to 1670°F (910°C) were employed during this 60 cycle test.

During the durability test, the CMC tiles were exposed to temperatures up to 1780°F and a transient through thickness gradient up to 490°F. The TPS peak temperatures on the hot side of the panels ranged from 750 to 1000°F during the 60 cycles. The through thickness delta T ranged from 450 to 650°F, varying with TPS location and cycle number.

No damage, such as cracks or chipping, was observed in the CMC tiles after completion of the testing. However, one tile warped during the durability test and was replaced after 43 of 60 cycles. No externally observable damage was found in this tile. No failure of the CMC fasteners occurred, but damage was observed. Cracks and missing material occurred, only in the fastener head region. No indication of damage was observed in the T-foam acoustic absorbers. The SiC foam acoustic absorber experienced damage after about 43 cycles. Cracking in the TPS occurred around the attachment holes and under a vent. In spite of the development of damage, the TPS maintained its insulative capability throughout the durability test.

The durability test results demonstrate damage-tolerant CMC tile, CMC fastener, TPS, and T-foam absorber designs for the combined thermal and acoustic engine nozzle environment.

## 1. INTRODUCTION

### 1.1 Background

NASA conducted a major government-industry research effort called the High Speed Research (HSR) program. The program objective was to establish the technology foundation to support the production of an environmentally acceptable, economically viable, 300 passenger supersonic aircraft, referred to as the High Speed Civil Transport (HSCT). Within HSR, the Enabling Propulsion Materials (EPM) program was charged with demonstrating the technology feasibility of advanced materials for critical propulsion components of the HSCT. One of the major technical focus areas in EPM was development and demonstration of materials for the exhaust nozzle.

The EPM Exhaust Nozzle program was charged with demonstrating the technology feasibility of advanced materials and components for a lightweight, low noise exhaust nozzle for the HSCT. The main objectives of the program were to: 1) demonstrate the ability to design and manufacture exhaust nozzle components from advanced materials, 2) demonstrate the durability of the candidate materials for required life, and 3) demonstrate the applicability of these components in the nozzle environment.

One technology under development for noise attenuation was the acoustic liner system. The Exhaust Nozzle program evaluated ceramic matrix composite (CMC) structural acoustic tiles and woven ceramic fiber, non-structural acoustic bulk absorbers for light weight/high temperature sound absorption and thermal blankets for a high temperature resistant thermal protection system. These three components make up the acoustic liner system. A schematic of the acoustic liner system within the HSCT Nozzle is shown in Figure 1. The life requirement for the acoustic tiles and the thermal blankets is 9000 hours.

## **1.2 Test History of Acoustic Liner System**

Four hot acoustic tests were conducted to assess the viability of the acoustic liner system in the anticipated exhaust nozzle environment. The first three tests are summarized below. The fourth test, the durability test, is the subject of this report.

### **1.2.1 Hot Acoustic Rig Test at WPAFB (Preliminary Evaluation)**

The first test conducted was a proof test of the acoustic tiles and thermal blankets using the Combined Environment Acoustic Chamber (CEAC) at Wright-Patterson Air Force Base (WPAFB). The primary purpose of this test was to validate and screen CMC acoustic liners in a simulated engine environment prior to an engine test in an advanced nozzle termed the Large Scale Model, which will be described below. Four CMC liners, each with a slightly different configuration, were evaluated. The bulk acoustic absorber was not incorporated into this test. This test configuration was used in order to expose the CMC liners to the most severe acoustic conditions, that is, without any potential beneficial vibration damping due to the presence of the bulk absorber. The thermal blankets were included in the test. The test plan is detailed in reference 1 and the test results in reference 2. The testing was successfully completed in November 1997.

### **1.2.2 Large Scale Model, Build 1 Test**

Three of the CMC acoustic tiles, along with one configuration of the acoustic absorber, were then tested in the Large Scale Model, Build 1 (LSM 1) test. The LSM 1 test consisted of a 56% scale HSCT nozzle exposed to the exhaust of an F100-229 engine. This test was conducted under the auspices of the HSCT Critical Propulsion Components (CPC) Nozzle Program (ref. 3). The main objectives of this test were to determine the acoustic attenuation of the CPC nozzle design and to verify noise abatement predictions in the nozzle environment during take off conditions of the HSCT.

The baseline LSM 1 design included metallic acoustic tiles and the bulk absorber developed under the EPM nozzle program. The LSM 1 test lasted 71 hours. The CPC Nozzle program was able to accommodate three CMC acoustic tiles for the last 21.5 hours of the test in place of eight of the smaller metallic tiles. The CMC tiles and the bulk absorber were successfully tested, with no externally observable damage. More details regarding the EPM nozzle contributions to the LSM 1 test can be found in references 4 and 5.

### **1.2.3 Tile-Off Hot Acoustic Test**

As shown in Fig. 1, the primary role of the thermal blanket is to keep the nozzle structure temperature within acceptable limits for the structural material,  $\gamma$ -TiAl. In this application, the thermal blanket, or thermal protection system (TPS), has to meet this requirement in the event of the loss of CMC acoustic tiles and bulk acoustic absorber. In this scenario, the TPS would be exposed to the exhaust gas stream. Under normal application, the CMC tiles and the bulk acoustic absorber reduce the hot side temperature of the TPS relative to the gas stream temperature.

To assess the ability of the TPS in this tile-off situation, a second hot acoustic test was conducted utilizing a hot acoustic test facility at Pratt & Whitney in Florida. Two 12-hour tests were conducted with a 2' x 2' section of TPS covered with a 1' x 2' section containing CMC acoustic tiles and the acoustic absorber. The testing also evaluated two TPS joint designs. The TPS successfully demonstrated the ability to survive this tile-off situation, and an optimum TPS joint design was selected. Details can be found in reference 6.

## **2.0 HOT ACOUSTIC DURABILITY TEST OF THE ACOUSTIC LINER SYSTEM**

After the successful completion of the previous hot acoustic tests (including the LSM 1 engine test), a durability test of the acoustic liner system was conducted. The purpose of this report is to document the results of this test.

### **2.1 Test Objectives**

The objectives of the durability test were to: 1) measure the dynamic behavior of the CMC acoustic tiles subjected to acoustic loading at ambient temperature, and 2) obtain durability information by accumulating thermal cycles concurrent with acoustic exposure on the CMC acoustic liner tiles, bulk acoustic absorbers, and thermal protection system.

## 2.2 Components Tested

### 2.2.1 CMC Acoustic Tiles

The acoustic tiles tested were 12"x12" flat panels, as shown schematically in Figure 2. The tile material is a woven silicon carbide fiber (SiC) fiber-reinforced Si-N-C-O matrix composite (SiC/SiNC) manufactured by Dow Corning under the trade name of Sylramic™ S201 using the polymer impregnation and pyrolysis (PIP) method (reference 7). The Si-N-C-O (or commonly designated SiNC) matrix is reinforced by eight plies of ceramic grade Nicalon™ fabric (8 harness satin weave) in a quasi isotropic layup [0/90/+45/-45]<sub>2S</sub>. Fiber volume fraction was approximately 45%. The density was 2.1g/cm<sup>3</sup> and the composite contained open porosity of about 5%. The eight plies result in an average thickness of 0.1 inch.

Each tile contains six attachment holes in built-up areas as shown in Figure 2. These built-up areas consist of additional eight plies (sixteen plies total in these regions) and can be continuous along the attachment holes, or localized around the attachment holes.

An important feature of the tile design is the open area, which allows the acoustic energy of the exhaust gas stream to pass through the tiles and be attenuated by the acoustic absorber (see Fig. 1). Tiles with percentage open area (POA) of 25, 30 and 35 %, in the form of a hexagonal array of holes, were manufactured, with 35 % preferred for the ability of tiles with higher open areas to yield a greater acoustic attenuation from the acoustic liner system. Holes having 0.07 and 0.10 inch diameters were evaluated.

Four CMC tiles (Table 1) each with a slightly different configuration, were tested. The layout of the tiles is shown in Figure 3. Three of the four CMC liners (DC 109A, DC 109B, and DC 105) were previously subjected to a total of 29 hours in a hot acoustic environment, which included 7.5 hours during the preliminary hot acoustic test and 21.5 hours during the LSM 1. The fourth CMC liner (DC 111A) is the first tile tested with 0.1" diameter holes. Also, to approximate a fastener configuration planned for future acoustic tests, only four fasteners were used on DC 111A. In this tile, the fasteners were installed in the outer four fastener holes, and the central two holes were not used.

**Table 1. CMC Liners tested during the Hot Acoustic Durability Test.**

CMC Liner ID	Buildup	POA	Acoustic Hole Diameter	Location in Test	Note
DC 109A	Local	30	0.07"	1	
DC 111A	Local	35	0.10"	2	4 fasteners used for attachment
DC 109B	Local	35	0.07"	3	
DC 105	Continuous	35	0.07"	4	
DC 103A	Local	30	0.10"	n/a	spare

### 2.2.2 Thermal Protection System

The thermal protection system (TPS) consisted of a five-layer construction and was in the form of 1' x 2' panels. A Haynes 214 foil, 0.005" thick, sealed the outside of the TPS. Two inner insulative HSA ceramic paper layers were separated by a 0.002" thick Haynes 214 foil layer, which served as a radiation barrier. Sealing between the two panels was accomplished with a one-inch overlap seal joint. TigHitco manufactured the TPS panels, designated TMS NC 1420 Serial Numbers 1 and 2. More details regarding the TPS design can be found in reference 8. Figure 4 is a schematic of the TPS configuration and Figure 5 is a photograph of the as-received TPS panels.

### 2.2.3 Acoustic Absorber

The acoustic absorber, which was down selected by the EPM Nozzle team, was termed the T-foam and was manufactured by Techniweave, Inc. The T-foam consisted of a 3-D weave of Nextel 440 fibers within a sol gel infiltrated aluminum oxide matrix. The volume fraction of fibers was 5.5 % maximum. The T-foam was manufactured into net shape, with no machining required. A photograph of the as-manufactured T-foam is shown in Figure 6.

Several configurations of the T-foam were tested in order to assess the durability of designs being considered for use by the CPC Nozzle program in future nozzle tests. The 11.7 lbs/ft<sup>3</sup> T-foam bulk absorber was tested for approximately 71 hours under the metal tiles during the LSM 1 test as discussed above. This same 11.7 lbs/ft<sup>3</sup> T-foam configuration and two lighter T-foam bulk absorber configurations were selected for this durability test (Table 2). One of the lighter configurations contained three sheets of Al<sub>2</sub>O<sub>3</sub> paper, which were interwoven in the Nextel fiber array. Based on testing by the CPC Nozzle team, this configuration had the best acoustic attenuation properties. An alternate acoustic absorber, a 15.4 lbs/ft<sup>3</sup> SiC foam, was also tested. The layout of the acoustic absorbers in the test frame used during the acoustic testing is shown in Figure 3. Note that the Ultramet SiC foam was only subjected to the durability test. During the ambient testing, a 9.5 lbs./ft<sup>3</sup> T-foam panel was installed.

**Table 2. Absorbers tested during the Hot Acoustic Durability Test.**

Bulk Absorber ID	Fiber/matrix ratio	Density (lbs/ft <sup>3</sup> )	Location in Test	Notes
T-foam, 1973-30	7/1	8.8	1	
T-foam, 1973-41	7.1/1.1 w/paper	8.2	2	
Ultramet SiC foam	n/a	15.4	3	only tested during durability test
T-foam, 1973-26	9/3	11.7	4	4
T-foam, 1973-28	9/1	9.5	3	tested during ambient exposure only

### **2.2.4 Acoustic Liner Fastening System**

The CMC tiles, the acoustic absorbers, and the TPS were attached to the test hardware back structure by means of a CMC lug, a  $\text{Si}_3\text{N}_4$  bushing, and assorted metallic hardware, as shown in Figure 7.

The CMC lug was machined from a 16-ply SiC/SiNC composite plate. The fiber cloth layup was the same used for the CMC tiles, quasi-isotropic. The lug included a transition radius from the straight portion to the tapered head (not shown in Figure 7). Each CMC tile contained 6 tapered holes that were machined in the build-up areas. The CMC lugs were inserted in these holes, passed through the T-foam, the TPS, and the back structure of the test fixture. A hole near the end of the lug enabled a metallic threaded sleeve to be held in place with a pin after installation of the lug. The  $\text{Si}_3\text{N}_4$  bushing was installed between the TPS and the CMC liner. A belville washer and a nut, initially torqued to 10 in-lbs., were used to secure the CMC lug. More information on the design of the CMC fastening system can be found in reference 9.

## **2.3 Test Facility**

The Combined Environment Acoustic Chamber (CEAC) at Wright Patterson Air Force Base was used for the durability test. An overall view of the system can be seen in Figure 8. It combines high temperatures and acoustic loads to simulate harsh environments experienced by hypersonic aircraft structures, exhaust washed structures, and thermal protection systems. This test system is essentially a progressive wave tube that uses quartz lamps to apply heat to test specimens while being acoustically excited.

The progressive wave tube has a 12" by 48" cross section. Twelve electro-pneumatic noise modulators generate the acoustic energy of the progressive wave tube. Two compressors produce the air needed by the modulators. The sidewalls of the test section are made of water cooled 6061-T6 extruded aluminum. Sidewalls areas directly exposed to the quartz lamps are polished to mirror clarity in order to reflect more radiant energy to the test specimen. A 1000 gpm pump pushes water through passages in the aluminum to cool the side walls and the lamp bank reflectors. The opening of the specimen side is 110" long by 48" high. The CEAC uses six banks of 6000 watt quartz lamps to heat test articles. Each bank or zone has 81 lamps for a total of 486 lamps. More details regarding the capabilities of the CEAC can be found in reference 10.

Test articles are mounted on a cart. Figure 9 shows the acoustic liner system on the cart prior to testing. Note that in this figure, only the hot gas side of the CMC tiles can be seen, as well as a portion of the frame used to hold the acoustic liner system.

## **2.4 Test Conditions**

The testing consisted of two parts: 1) a short term ambient exposure to assess the response of the CMC acoustic tiles to the acoustic loading and 2) a 75 hour durability test conducted using a thermal-acoustic cycle.

### **2.4.1 Acoustic Loads**

The acoustic loading for both portions of the test was selected based on the anticipated sound pressure levels during the service cycle of the HSCT nozzle. The predicted acoustic spectrum for the full scale (product size) nozzle, during the take-off conditions ranged from approximately 136 to 139 dB/Hz in the frequency range of 500 to 2000 Hz, depending on location within the nozzle (reference 11). For supercruise conditions, the highest predicted sound pressure level was 131.5 dB/Hz (reference 12). Based on these predictions by the CPC Nozzle Program, sound pressure levels of 136 and 139 dB/Hz in a frequency range of 500 to 2000 Hz were selected to subject the acoustic liner components to the highest anticipated loads.

### **2.4.2 Ambient Testing**

Two ambient temperature acoustic exposures were conducted. The first exposure was used to assess the dynamic response of the CMC acoustic tiles without the presence of the bulk acoustic absorber and the TPS. The second exposure tested the CMC tiles with the bulk absorbers. For each ambient acoustic exposure, the following procedure was used:

1. Sine Sweep (approximately 30 minutes), as described below.
2. 136 dB/Hz for 15 minutes.
3. Sine Sweep (approximately 30 minutes).
4. 139 dB/Hz for 60 minutes.
5. Sine Sweep (approximately 30 minutes).

The procedure used for the sine sweeps was as follows. A constant sound pressure level of 130 Hz was imposed on the test articles, starting at a discreet frequency of 100 Hz. The frequency level was changed slowly while maintaining the same sound pressure level, until a maximum of 1000 Hz was obtained. During this frequency sweep, the strain gage data was acquired. The data acquired prior to the 136 and 139 dB/Hz exposures is considered to be the response of the undamaged CMC tiles. Any shift in the frequency corresponding to the peak strain response or an increase in strain response is often associated with component damage. In addition, the damping factor (Q) of the acoustic tiles and fasteners can be determined with the strain gage data.

### **2.4.3 Thermal Acoustic Testing**

The durability testing involved subjecting the acoustic liner system to 60 thermal-acoustic cycles of 75 minutes duration, for a total exposure time of 75 hours. The cycle employed is shown in Figure 10. The portion of the cycle conducted at an acoustic load of 139 dB/Hz was intended to approximate a take-off condition, and the rest of the cycle approximated the supercruise portion of the engine service cycle. At a cycle time of 10 minutes, rapid heating was employed to obtain a through-thickness thermal transient gradient in CMC tiles of 490°F after 8 seconds, to simulate the maximum transient gradient anticipated during the service cycle of the tiles.

## 2.5 Instrumentation

Six strain gages were attached to each CMC tile as shown in Figure 11 to measure strains during the ambient acoustic exposures. The strain gage type was Measurements Group EA-06-031DE-120. The gages were attached to the webs between the acoustic holes and therefore did not bridge holes.

Prior to starting the durability testing, the strain gages were removed and Type K thermocouples were attached to the CMC tiles, as shown in Figure 12. The thermocouples were installed using alumina cement. The hot sides of the instrumented tiles were coated with a black high temperature paint to avoid surface temperature variations associated with differences in emissivity.

Type K thermocouples were attached to the TPS as shown in Figure 13. These thermocouples were welded to the Haynes 214 outer foil.

## 2.6 Results

### 2.6.1 Ambient Testing

RMS strain gage data for each tile is shown in Figure 14 for the 136 dB/Hz exposure and in Figure 15 for the 139 dB/Hz exposure. Two data points are shown for each strain gage, one for strains measured in the CMC tiles without the bulk absorbers and the other for strains measured with the bulk absorbers installed. The presence of the acoustic absorbers did reduce the strain measured during the acoustic exposure in the CMC tiles relative to the exposure without the absorbers. Sine sweeps conducted both before and after the 136 and 139 dB/Hz exposures did not produce significant RMS strains (i.e. 30 microstrain and below) nor a shift in the frequency corresponding to the peak strain response, implying that no detectable tile damage occurred.

The RMS strain gage data in Figures 14 and 15 can be compared to the measured mechanical properties of SiC/SiNC. The SiC/SiNC composite's tensile proportional limit at room temperature is 8 ksi, as determined through acoustic emission measurements taken during a uniaxial tensile test (reference 13). The modulus is 14 MSI and the strain at the proportional limit is 2400 microstrain. The maximum RMS strains for each tile are shown in Figure 16. The peak RMS strains measured during the acoustic fatigue loading are considerably less than the composite's proportional strain. For CMC's exposed to non-oxidizing conditions, fatigue loading below the proportional limit typically yields runnout lives and no composite damage develops (reference 14), consistent with the conclusion above that the 139 dB/Hz exposure did not damage the tile.

The damping factors (Q values) were calculated for each tile and are reported in reference 15. The average Q value without the bulk absorbers installed was 28.4, and with the bulk, the average Q value was 15.2.



## 2.6.2 Thermal Acoustic Testing

The 75-hour durability test took three months to complete. Delays in completing this test involved the thermal-acoustic test conditions employed. The combination of frequency range and sound pressure levels employed was not used before in the CEAC facility. One result of operation under these conditions was repeated failures of the water cooling channels within the sidewalls of the CEAC. Time consuming failure analyses and repairs were required. A detailed, daily log of the test is given in Appendix I. Note that three major cooling system leaks occurred, after cycles 12, 22, and 40, which exposed the acoustic liner system to water while at high temperature.

An inspection by the WPAFB personnel after 43 cycles of testing revealed that one CMC tile (DC 105) had shifted and could not be moved back to its original location. The sealing lip on DC 105 would not slide under the two adjacent tiles, DC 109B and DC 111A. Tile DC 105 was then removed from the test and replaced with the spare, DC 103A.

### 2.6.2.1 Component Temperature Data

Figure 17 shows the temperatures measured in all four CMC tiles during test cycle 1. The temperatures of the CMC tiles were recorded only for the first cycle. The variations of temperature through the thickness and in plane can be seen. The temperature as a function of time during the transient heating portion of the first cycle is shown for all four tiles in Figure 18. The through-thickness thermal gradient in the four CMC tiles ranged from 388 to 486 °F at the end of the 8 second transient heating portion of this cycle.

Figure 19 shows the temperatures measured on the hot and the cold sides of the TPS panels during the first cycle. For clarity, the data shown is for one of the two TPS panels. Note that the temperatures on the cold side of the TPS increase at the end of the cycle, when the heating system is turned off and the acoustic loading was stopped. One possible explanation for this temperature increase may be due to the fact that the airflow through the system was much lower when the noise modulators were turned off. The reduction of the cooling air and subsequent cooling of the specimen holder through conduction to the TPS may have contributed to this rise in TPS temperature.

Figure 20 shows the maximum TPS temperatures for all twelve thermocouples from the beginning of the durability test through the last cycle (60). Also shown in the plot is an indication of cycles where unusual test events occurred, such as system water leaks and the observation of significant damage to the SiC foam acoustic absorber. No indication of a cycle by cycle increase or decrease of the temperatures was measured. However, increases of the peak temperatures occurred after the TPS was exposed to water during system cooling leaks during cycles 12 and 40. Also, note that the temperatures measured at the TPS joint (thermocouples 3,4, 9, and 10) are within the range of the temperatures measured away from the joints. This suggests that the insulative capability of the joint was similar to the baseline TPS for the test conditions used here.

The through-thickness temperature differential ( $\Delta T$ ) for the TPS as a function of cycle number is shown in Figure 21. An indication of cycles when an usual event occurred is shown as well. In general, the  $\Delta T$  was cyclic during the test. It increased during the first 12 cycles, decreased during the next 20 cycles, increased again until cycle 36, and then generally decreased until the end of the test. The cooling system water leaks that occurred during cycles 10 through 12 and cycle 23 may have contributed to the cyclic changes in the  $\Delta T$ .

#### **2.6.2.2 Examination of Tested Components**

The condition of the CMC liners, CMC fasteners, the bulk absorbers, and the TPS after the test was documented through photography. Radiography was used to document the condition of the CMC fasteners. Each component is discussed in the following sections.

**2.6.2.2.1 CMC Acoustic Tiles** – Figure 22 shows the four tiles after the testing was completed. In this view, the tiles were still installed in the frame used to hold the acoustic liner system to the specimen cart. More detailed views of the tiles after removal are shown in Figure 23. No damage, such as cracks or chips, was observed after a detailed examination of the tiles. The variation in color that can be seen on the hot side in both figures is due to a loss of the black constant emissivity paint and presence of alumina cement used to attach the thermocouples.

Each fastener hole was examined. Again, no damage, such as cracking or chipping, was found in any hole. An example of the typical condition is shown in Figure 24 for tile DC 111A. As stated above, only four fasteners were installed in this tile, leaving two fastener holes empty in order to evaluate the integrity of a 4-attachment design concept. Figure 24 shows a hole that contained a fastener (Figure 24a) and a hole that was not used (Figure 24b). The lightly colored (white) region in Figure 24a is possibly  $\text{SiO}_2$ , which is present in all the fastener holes that contained a CMC lug during testing. The white regions are not present in holes that did not contain a fastener.

As mentioned above, one tile (DC 105) was replaced after 43 cycles with the spare, DC 103A. A detailed inspection revealed warpage of tile DC 105 (Figure 25). No externally observable damage could be found in this tile. An ultrasonic inspection of this tile was inconclusive and could not detect any damage associated with the warpage. The tile warpage is believed to be the result of impingement of water on the hot tiles when a leak of the test facility's cooling water occurred.

**2.6.2.2.2 CMC Fasteners** – Thirty SiC/SiNC fasteners were used during the acoustic testing of the CMC acoustic tiles. Twenty-three of these fasteners had been used during previous acoustic testing. Eighteen of the thirty were inspected using X-ray imaging. Ten fasteners were returned to Pratt & Whitney for use during further acoustic testing of nozzle hardware and were not inspected. Of the eighteen fasteners that were inspected via radiography, five had cracks that occurred during previous hot acoustic tests. This pre-existing damage was detected via radiography performed after the preliminary WPAFB hot acoustic rig test and the tile-off hot acoustic test (reference 16).

The radiography conducted after the durability test showed cracks and missing material in the head region in ten of the eighteen fasteners. In some cases, this damage could easily been seen with the naked eye (Figure 26). A view of the nature of the cracking leading to this chipping in the head region of the fasteners is shown in Figure 27. This type of damage was also observed during hardware inspections during the test (reference 10).

The fastener damage likely originated in two ways. Damage initiation may have occurred during disassembly process. To remove a fastener, the nut and washer were first removed (Figure 7). Next, the threaded sleeve was removed by pressing out the pin. It is likely that high loads were imposed while pressing out the pin, especially in cases when the pin fit tightly in the fastener hole.

Another possible origin of damage was loosening of fasteners due to relaxation of tension imposed by the belville washer. Vibration of the fastener in the CMC panel attachment hole may have occurred in the loosened fasteners. Periodic inspections (as noted in Appendix I) during the hot acoustic test indicated that the torque on the fasteners was typically less than the initial 10 in.-lb. value.

Interlaminar shear failure occurred in one fastener (Figure 28). This fastener was removed after the completion of ambient testing. Even in the damaged state, the fastener carried the required axial load. A detailed analysis (reference 17) revealed that the damage was caused by a combination of misalignment and torsion loading, which probably occurred during the assembly and disassembly processes.

Small defects appeared in the x-ray images of four fasteners. These indications appear to be denser than the surrounding composite, suggesting that these defects have a higher atomic number than the SiC/SiNC fastener material. One of these fasteners was mounted and polished for detailed metallurgical examination, however, no unusual features were observed.

**2.6.2.2.3 Acoustic Absorber** – Figure 29 shows the four acoustic absorbers that were tested. The three T-foam panels had some discoloration, particularly on the hot side and outside edges, but no obvious damage could be seen. The lines seen on the hot side of the T-foam panels are regions where the thermocouples attached to the cold side of the CMC tiles contacted the T-foam.

Damage was observed in the Ultramet SiC foam bulk absorber. A section of the SiC foam was missing (Figure 29). The white deposits on the SiC foam absorber are insulation from the TPS (the TPS will be discussed in the next section). Some SiC powder was found in the CEAC after 43 cycles of testing and more extensive damage of the Ultramet absorber was noted after 52 cycles. Also, the fastener holes increased in size relative to the initial dimensions. Abrasion between the  $\text{Si}_3\text{N}_4$  spacers and the SiC foam caused this damage.

**2.6.2.2.4 Thermal Protection System** – A schematic showing the hot side of the two TPS panels is shown in Figure 30. This figure also indicates the position of the TPS relative to the tiles and the acoustic absorbers (see Figure 3). Cracking in the TPS was observed around the attachment holes (Figure 31) and under a vent on the hot side. No cracks were present on the cold side. The cracking appears similar to that observed in the TPS after the preliminary test conducted in the CEAC (reference 18). One difference is that fewer cracks exist in the panels tested during the durability test (6) than in those panels subjected to the preliminary test (10). In both cases, the cracks seem to have initiated adjacent to the weld region between the surface foil and the grommets. Imprints of the  $\text{Si}_3\text{N}_4$  spacers are present in the TPS subjected to durability test (Figure 32). These imprints exist around most attachment holes on the hot side.

The cause of the most of the cracking in the TPS panels was likely related to loosening of the CMC fasteners. The loosened fasteners enabled vibration of the  $\text{Si}_3\text{N}_4$  spacers against the TPS outer foil, resulting in the imprints (Figure 32) and cracking of the outer foil on the hot side (Figure 31).

Additional TPS damage occurred in the region of the TPS that was under the SiC foam absorber (Figure 33). Degradation of the Ultramet SiC foam bulk absorber probably led to the development of this damage. The hole in the TPS foil shown in Figure 33 exists in the region initially covered by the missing section of the SiC foam. Also, no HSA ceramic paper remained in the TPS adjacent to this hole and some was deposited on the SiC foam (Figure 29d).

Even though the TPS damage noted above appears similar to that which occurred after the preliminary hot acoustic test, the origin of the damage differs. A detailed analysis of the TPS panels tested during the preliminary hot acoustic test (reference 18) revealed several features that may have contributed to the cracking. Micro tears existed in the Haynes 214 foil in the regions around the grommets. This tearing was the result of the method used to punch the holes in the foil. Also, cross-shaped patterns of spot welds existed around each grommet. In some cases, small holes through the surface existed at the point of these welds. The presence of these features, along with the test conditions employed, likely led to the observed cracks in the TPS during the preliminary test. The preliminary hot acoustic test was a proof test of the acoustic tiles and thermal blankets. No acoustic absorbers were installed. The presence of the absorbers would have offered some dampening effect. For example, after other hot acoustic tests conducted at Pratt & Whitney in Florida, where the bulk was present, no cracking of the TPS was observed. Thus, the cracking was likely due to the presence of manufacturing features, such as weld defects and tears in the Haynes 214 foil, and undamped displacements occurring during the acoustic testing. The manufacturing process was subsequently changed to eliminate these undesirable features. The TPS panels subjected to the durability test were manufactured using the improved processes.

### 3.0 SUMMARY AND CONCLUSIONS

1. The CMC acoustic tiles were subjected to two 2 ¾ hour ambient temperature acoustic exposures to measure their dynamic response. One exposure was conducted on the tiles alone and the second exposure included the tiles and the T-foam bulk absorber. The measured tile RMS strains were small. With or without the T-foam absorber, the dynamic strains were below strain levels that would cause damage during fatigue loading.
2. After the ambient exposure, a 75-hour durability test of the entire acoustic liner system was conducted using a thermal-acoustic cycle that approximated the anticipated service cycle. During the durability test, the CMC tiles were exposed to temperatures up to 1780°F and a transient through thickness gradient up to 490°F. The TPS peak temperatures on the hot side of the panels ranged from 750 to 1000°F during the 60 cycles. The through thickness delta T ranged from 450 to 650°F, varying with TPS location and cycle number.
3. No damage, such as cracks or chipping, was observed in the CMC tiles after completion of the testing. However, one tile warped during the durability test and was replaced after 43 of 60 cycles. No externally observable damage was found in this tile.
4. No failure of the CMC fasteners occurred, but damage was observed. Cracks and missing material occurred, only in the fastener head region.
5. No indication of damage was observed in the T-foam acoustic absorbers. The Ultramet SiC foam acoustic absorber experienced damage after about 43 cycles. A section of the SiC foam was missing and damage occurred in the fastener holes.
6. Cracking in the TPS occurred around the attachment holes and under a vent. Additional damage existed in the region of the TPS that was under the Ultramet SiC foam. In spite of the development of damage, the TPS maintained its insulative capability throughout the durability test.
7. The durability test results demonstrate damage-tolerant CMC tile, CMC fastener, TPS, and T-foam absorber designs for the combined thermal and acoustic engine nozzle environment.

### ACKNOWLEDGEMENT

The work described in this report is the result of the collaboration of many individuals, including: Joe Grady, and Kang Lee of NASA Glenn Research Center; Bob Warburton, Beth Bates, Bob Miller, Dave Machen, and Ramon Mayor of Pratt & Whitney Aircraft Engines; Srimi Gowda, Mohammed Salikundin, and Joe Begavich of General Electric Aircraft Engines; Arnel Patia, Ron Crumbacher, and Ken Wentz of Wright Patterson Air Force Base.

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## **APPENDIX I**

### **High Speed Civil Transport/EPM Nozzle Program**

#### **CEAC Facility Run Log for Durability Test (Elevated Temperature Cycles Only)**

Recorded by Arnel Patia and Ron Crumbacker of WPAFB

**(June 10, 1998 to Sept. 11, 1998)**

##### **Serial Number/Date**

Note: The first three digits of the serial numbers indicate the day of the year, and the fourth is the run number for a particular day.

1618/ 10 June 98: HSCT facility check out

1628/: Thermal cycle set up (heat rise trial). Cycle #1.

1630/: The system shut down due to inadequate cooling due to a water tower problem after completion of 1250°F dwell period of cycle 2.

1631/: Completed cycles #2, 3 & 4. Note: When technical difficulties with the facility cause a shut down, the run either has to be restarted all over again or tacked on (piggy backed) with the following run. This is caused by the heater control system's inability to be started mid-cycle. For example, cycle #2 was piggy backed during cycle #3 by simply setting a time hold or dwell during cycle #3. This meant that certain portions of the temperature ramps were programmed to run twice as long as their normal cycle thereby finishing cycle #2 and #3 at the same time.

1761/: Cycles #5, 6 & 7. Stopped due to a TC (C1CENF) running cold. Stopped at 1250°F for cycle 6. Also, cycle 6 was abbreviated and the tiles were not heated to 1670°F. For cycle 7, switched to a different control TC (C1CNEF). Completed the 1250°F hold (dwell) only and did not heat to 1670°F. Found 47C bad.

1762/: Cycle #8. The hold at 1670°F was conducted for 1½ hours (versus the specified hold time of 30 minutes) in order to complete the required dwell time at the maximum temperature for the cycles conducted to date. Note that the maximum tile temperature during cycles 6 & 7 was 1250°F and this hold was intended to compensate for the lack of high temperature hold time.

1771/: 26 June: Cycle #9. The thermal cycle was conducted through the transient-heating portion three times and then stopped. Cycle 9 was then conducted in its entirety after that time. Also, switched to CMC temperature control with TC HSCT-2 after completion of



cycle 9 (upstream lamp side middle). A chamber panel leaked and necessitated re-welding the cooling channels closed.

1801/1802: 29 June: Cycles #10 and #11 completed. At the beginning of cycle #12, a significant water leak occurred inside the chamber itself. (It was noted that the TCs were not responding to the lamps – they were reading too cool for the known conditions inside the chamber). The water, itself, was acting as a coolant on the TCs. The test was aborted and the chamber checked for damage.

1891/: 08 July: The test article (per instructions from Mike Verrilli) was heated to 200 DEGF for 2 hours before continuing into cycle #12. This was done to dry out any residual moisture in the bulk absorber. (The TCs were repainted and RTV was placed on the damaged weld).

1901/: 09 July: Cycle #13. Ramped to 1670°F and then stopped prior to conducting the dwell. This was done because the RTV repair job did not work, and therefore water began to leak again. Testing stopped in order to repair weld.

1981/: 17 July: Cycle #14. Power loading was reduced 2%.

2101/: 29 July: Cycle #15. TC HSCT2 was used for control.

2111/: 30 Jul: Cycle #16. No significant changes to the test article have been observed.

2121/: 31 July: Cycle #18 and 19 (lost modulator valves 3 and 6).

2122/: 31 July: Cycles #20 and 21. Valves 2 and 4 failed. Stopped after finishing 1670°F ramp.

2151/2152: 03 Aug: Finished last part of cycle #21. Continued into cycle #22 (2151). The TCs were reading low due to the black paint wearing off them. During the start of cycle #23 (2152), the middle Al panel started to leak and the cycle was stopped. Upon test article inspection, it was discovered that CMC face sheet #4 was not under (shingled) under panel #3. Panel 2 was about 80% off panel #1. (The panels had shifted due to lose attachment pins). The test article was removed from the frame. The safety wire was removed, and the nuts re-torqued to the specified 10 inch-pounds.

2191/: 07 Aug: Cycles 24 and 25.

2192/: Cycles #26 and #27. Stopped ramp at 1670°F of cycle 27 due to interference from Civil Engineering activity in the building. Therefore, cycle 27 was shortened due to interruption in facility operation. NOTE: (After cycle #26, the bottom panel slipped again.)

2221/: 10 Aug: Finished cycles #27, #28 and #29.

2222/: Cycles #30, #31.

2291/: Cycle 32

2301/2302/2303: Cycle 33 interrupted after completion of 1250°F hold period. Upon attempting to conduct this cycle again in its entirety, it was stopped three more times during the transient heating portion of the cycle. Cycle 33 was subsequently completed during the fifth attempt. Cycle 34 was started and stopped during 1670°F hold period.

2371/: Cycle 35 was completed. Additional time was added during the 1670° hold period to account for the abbreviated hold time at this temperature which occurred during cycle 34.

2381/: 26 Aug: Cycles #36, #37 #38. De-ionizing water went out due to low water level and therefore the testing was stopped. Also lost valve #1, 7 & 10.

2382/: Cycle #39. Found manifold leak at end of test. Repainted TC on panel 4.

2391/: 27 Aug: Cycle 40 completed (lost valve #5). Started cycle 41 and failed valve #9. Also, a cooling hose blew off the upstream reflector plate on the specimen side. Cycle 41 was stopped due to these problems while holding at 1250°F. Needed to clean some of the lamps that got wet when the cooling hose failed. Cycle 41 needed to be re-done.

2441/: 01 Sept: Baked at 200°F for two hours to dry out the test articles prior to continuing the testing. No record taken.

2451/: 02 Sept: Cycles #41 and #42. Used HSCT\_4.dat to control. Test was stopped due to a water leak.

2452/: Cycle #43. Encountered noise (or drop out) on this cycle. Lost amp. Some more clipping observed at fasteners. CMC tile (DC 105) had shifted and could not be moved back to its original location. This tile was then removed from the test and replaced with the spare, DC 103A.

2511/: 08 Sept: Cycle #44 aborted with three valves out.

2512/: 08 Sept: Cycle #44. Lost valve #10. Reset the NEFF (heat control system computer) cards. No more drop out was encountered. Cycle #45 – lost lamps in 2A and 2C.

2513/: Cycle #46 and #47.

2514/: Cycle #48. Fastener damage is more noticeable now.

2521/: 09 Sept: Cycle #49. Lost lamps in 2C and valve #5. Cycle #50 was aborted due to a fire alarm going off. After alarm (evacuation) cycle #50 was re-started. Did not get record until ramping to 1250°F. Aborted due to two lost valves.

2522/: Cycle #50 started again – abort due to blown fuse in 1A. Temperature control via the NEFF computer was erratic. The control appeared to switch off and then restart. The desired peak temperatures were obtained, but significant control deviations occurred. Cycle #50 finished. During cycle 51, temperature control problems occurred as well. Component temperatures were generally lower due to paint coming off ceramic tile thermocouples, thus affecting the emissivity of the CMC panels and their temperature.

2531/: 10 Sept: Cycle #52 aborted on ramp up to 1250°F due to water leak. The leak was repaired, and the testing was restarted. Cycles 52 & 53 were completed.

2532/: The SiC foam acoustic absorber (GE's bulk absorber) had damage in as much as ¼ of its area. Wire was inserted through the holes in the CMC tile #3 and back-up blanket to determine that a void had formed in the SiC foam absorber. Dust (from the SiC foam) has been noticed on the floor of the CEAC for a few cycles previous to this one. It was known that the foam had been deteriorating, but it was not known until now that a void had been forming too. Panel #3 (the one on top of GE's material) can be "rattled" by hand. Panel #3 was subsequently re-torqued after cycle #53. SCR went down. Primary was off. Main breaker at VAAO went down because a screw touched the hot (electrically) bus bar. Cycle #54 aborted.

2541/ 11 Sept: Cycle #54 completed. Ceramic from the TCs was found lying on the floor. Five grams of SiC foam was swept off the floor. Only a small "chunk" of SiC remains in the lower left-hand diagonal corner (when viewed from the front of the panel array) behind panel #3. Cycle #55 completed.

2542/: Cycle #56 completed. Lost TTOPUPH and TBOTUPH (TPS thermocouples).

2542/: Cycle #57. Swept up 29 grams of SiC foam dust.

2543/: Cycles #58 and #59 completed.

2544/ 11 Sept. 98: Cycle #60 completed. END OF TEST.

Thermal Blanket

Bulk Ceramic Absorber

CMC fastener

CMC Acoustic Tile

$\gamma$ -TiAl Flap Structure

The technical drawing illustrates the dimensions and cross-sections of a PCB layout. The main layout shows a rectangular board with overall dimensions of 12.240 by 12.280. It features six square components arranged in two rows of three. Key dimensions include a .500 TYP spacing between components, a 6.000 spacing between rows, and a 3.120 spacing from the bottom edge to the first row. A 1.000 TYP spacing is shown between the bottom row and the bottom edge, and a 3.140 spacing is shown between the bottom row and the bottom edge. A 3.000 TYP spacing is shown between the bottom row and the bottom edge. A .190 dimension is shown at the top right, and a .159 dimension is shown at the top right. A .220 TYP dimension is shown between the top row and the top edge, and a .450 TYP dimension is shown between the bottom row and the bottom edge. A .030 CHAMFER BOTH SIDES dimension is shown at the bottom right. A 10.0° angle is shown at the bottom right, and a 45.0° angle is shown at the bottom right. The cross-sections, View A and View B, show the internal structure of the board, including the core, prepreg, and copper layers. View A shows a cross-section of the board with a .100 dimension. View B shows a cross-section of the board with a .200 dimension. The lay-up section shows the internal structure of the board, including the core, prepreg, and copper layers, with a 10.0° angle and a 45.0° angle.

20

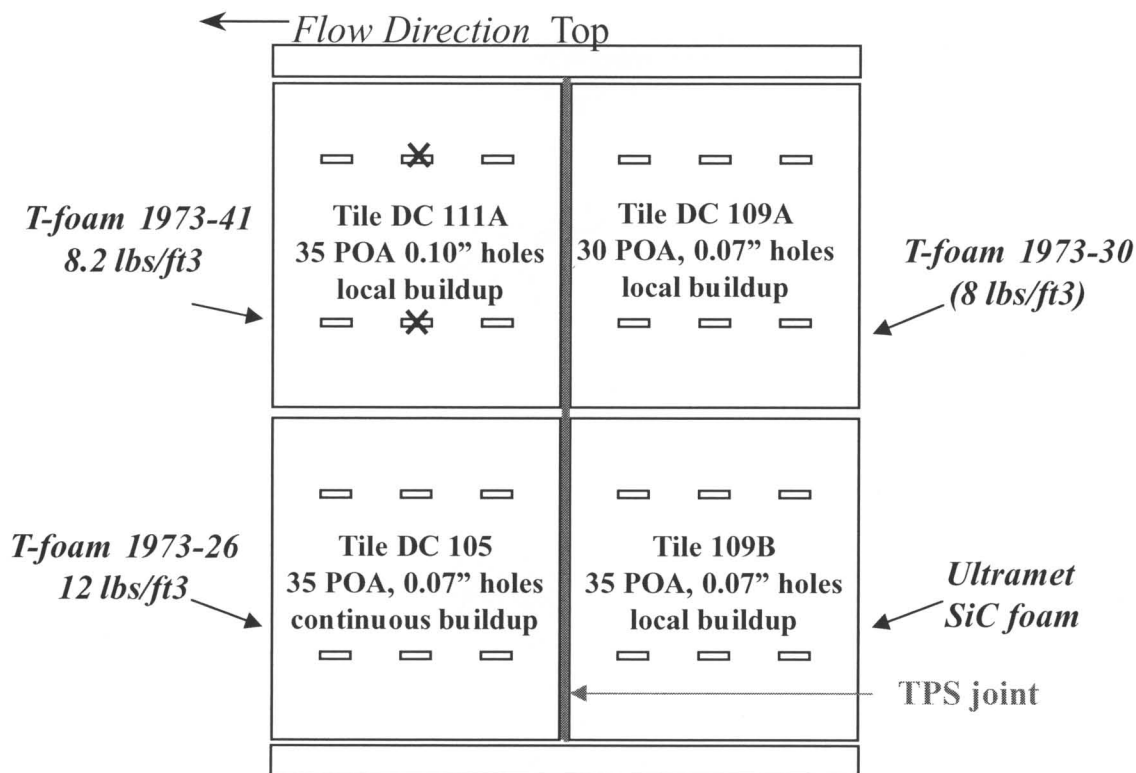


Figure 3 – Schematic showing the location of the individual CMC tiles, the bulk acoustic absorbers, and the TPS in the CEAC test frame.

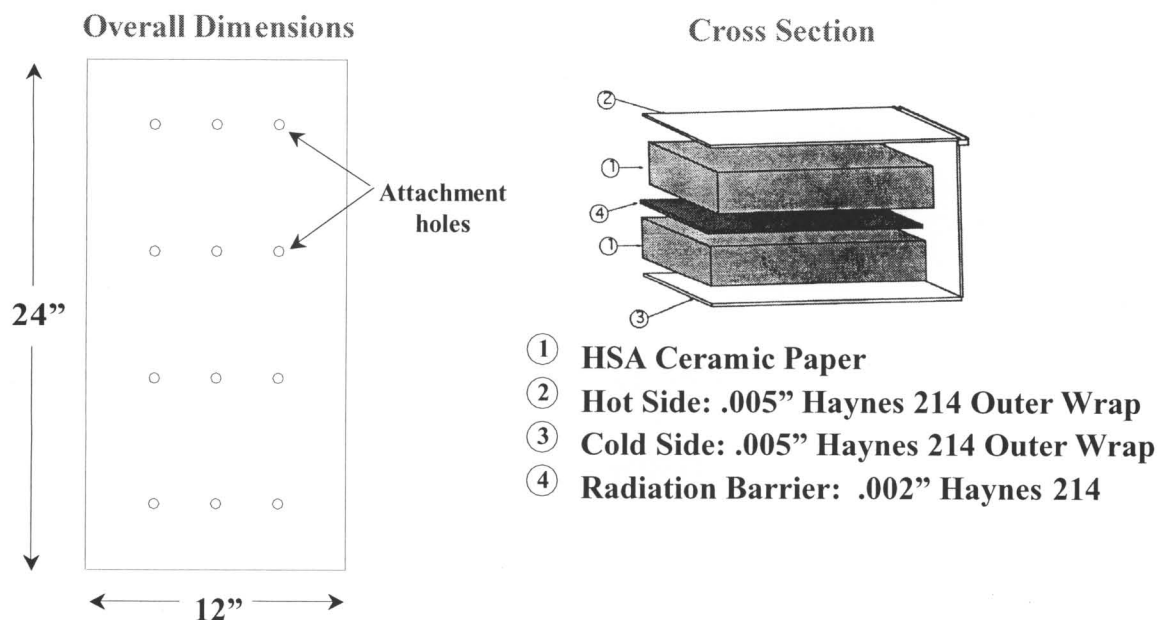


Figure 4 – Schematic of TPS configuration and its cross section. Two 12" x 24" TPS panels were tested.

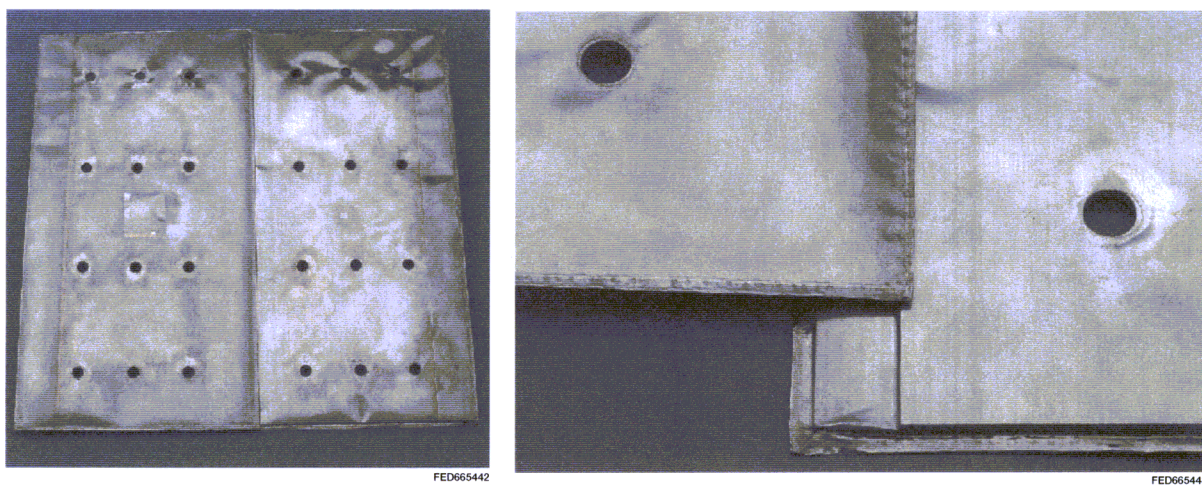


Figure 5 – Photographs of as-received TPS panels with the 1” overlap joint.

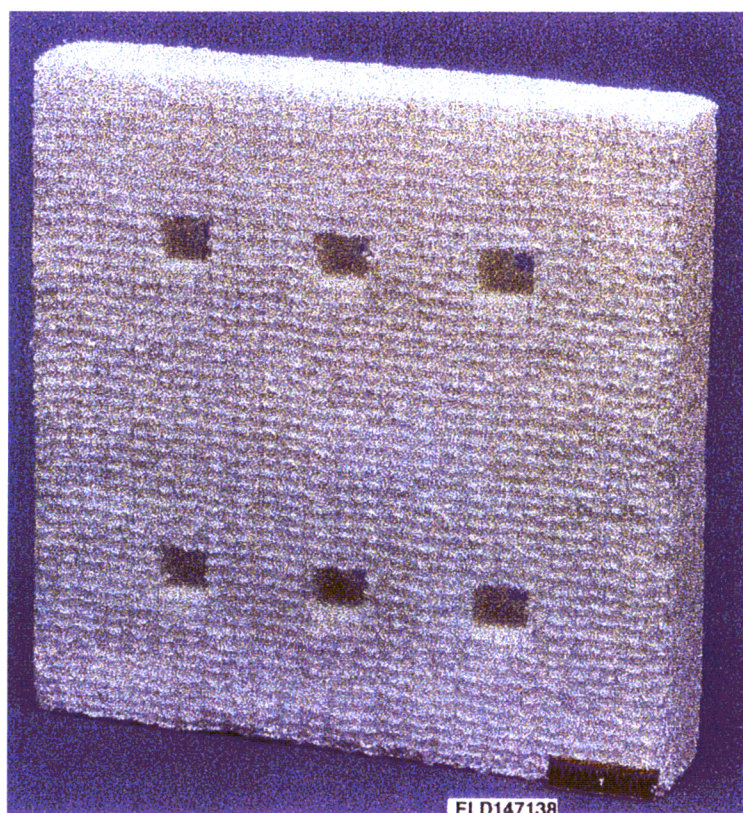


Figure 6 – Photograph of the as-manufactured T-foam.



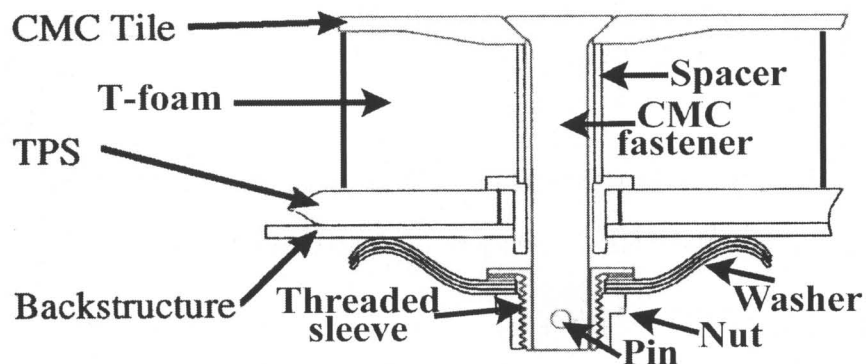


Figure 7 – Schematic of fastening system used for acoustic liner system.

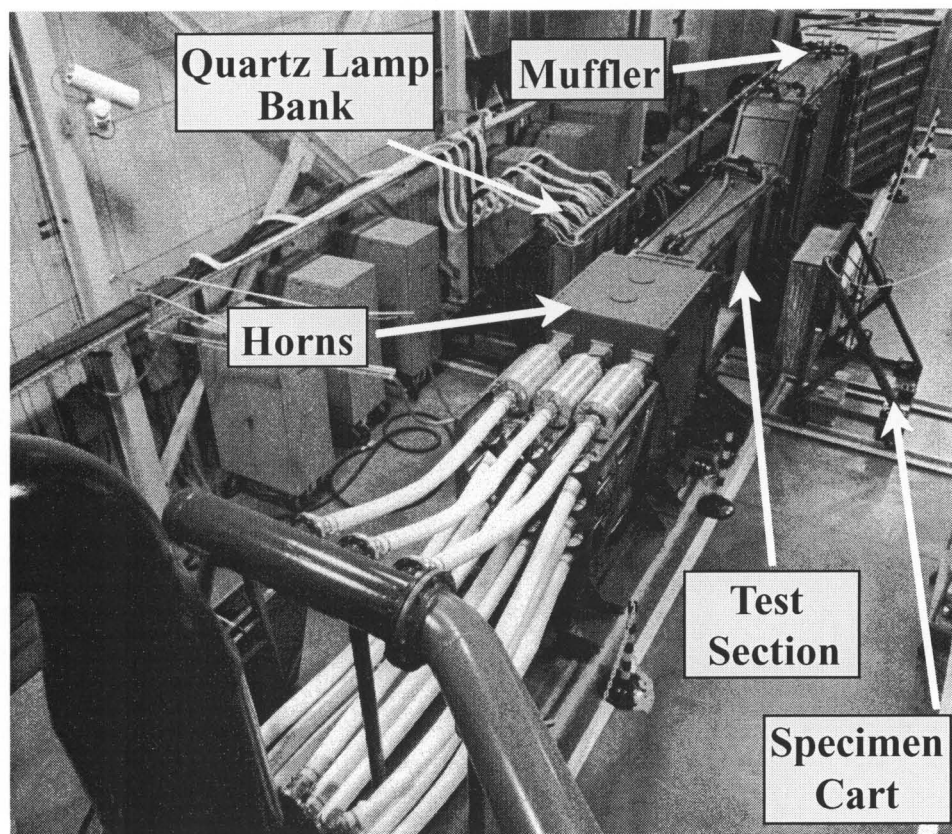


Figure 8 – Overall view view of the WPAFB Combined Environment Acoustic Chamber.

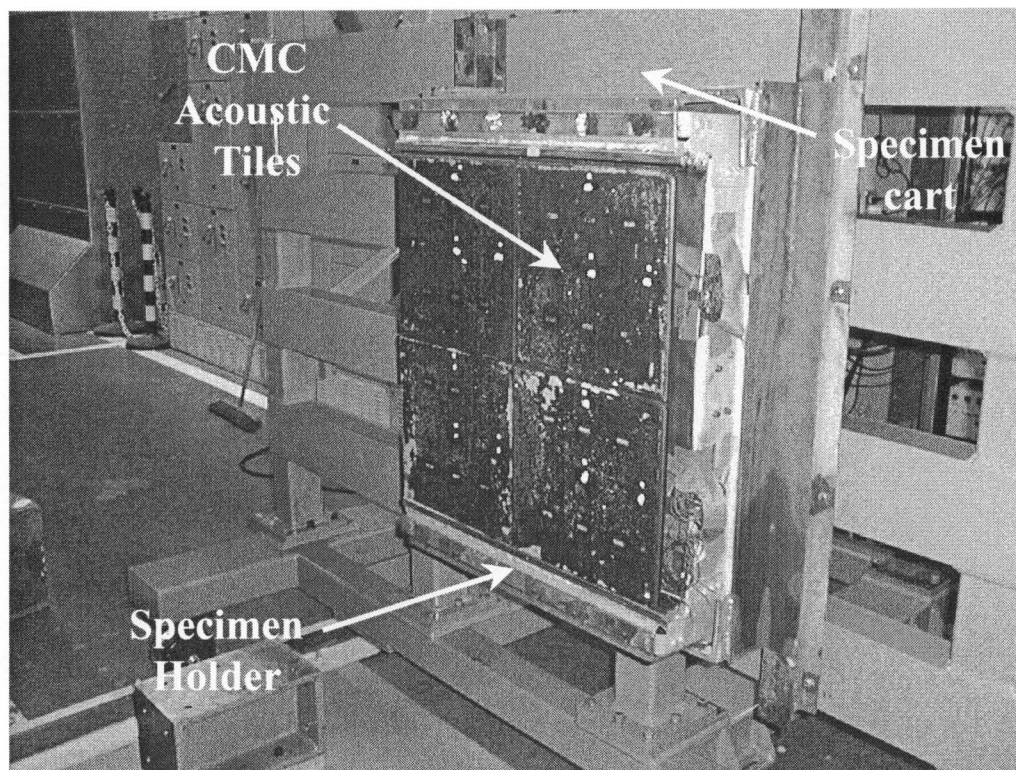


Figure 9 – View of acoustic liner system in the specimen holder on specimen cart used in the CEAC.



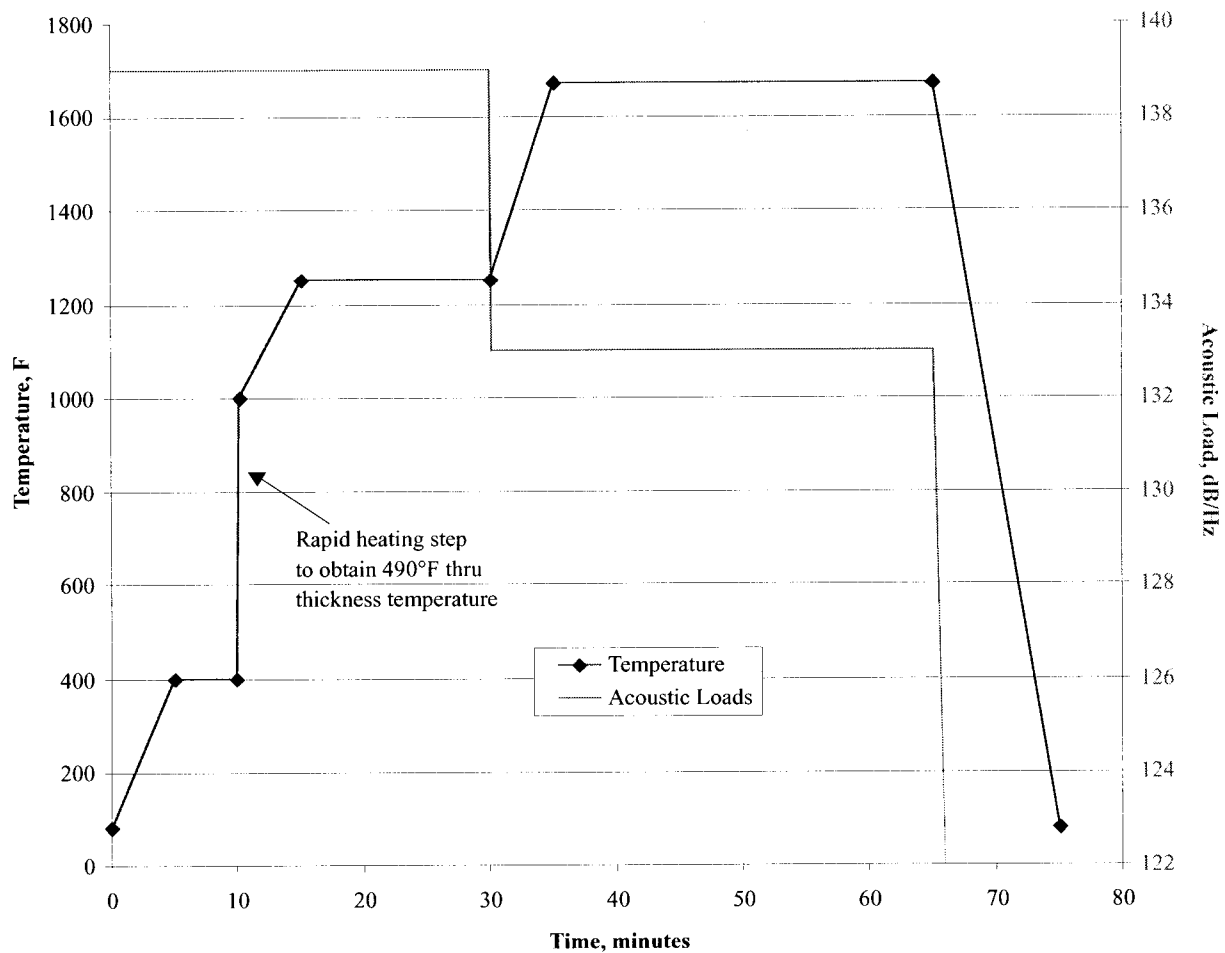


Figure 10 – Thermal-acoustic cycle employed for testing of the acoustic liner system. The temperature cycle is based on the temperature measured on the hot side of the CMC acoustic tiles.

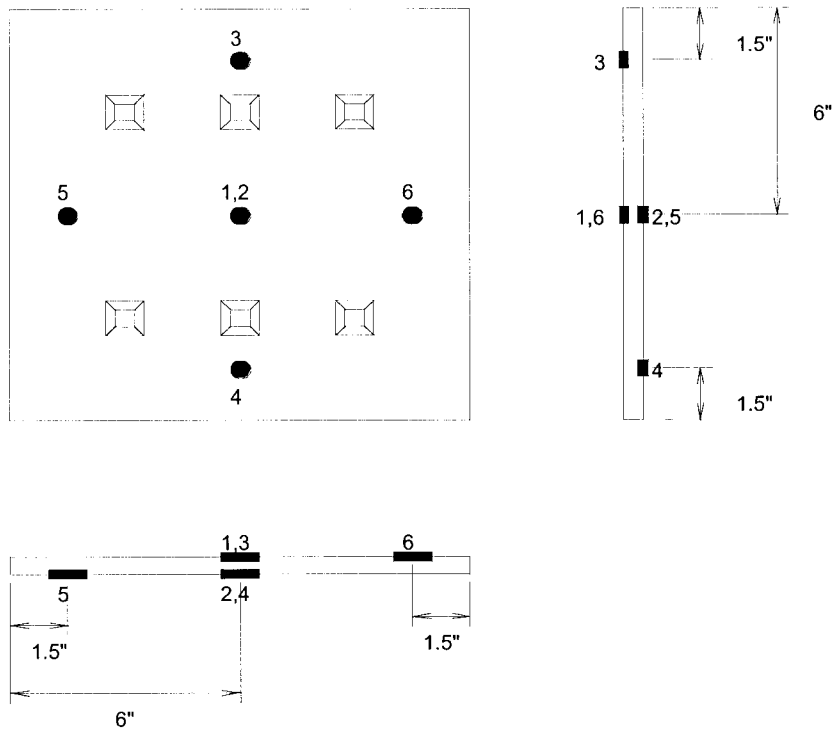


Figure 11 – Location of strain gages attached to each CMC acoustic tile.

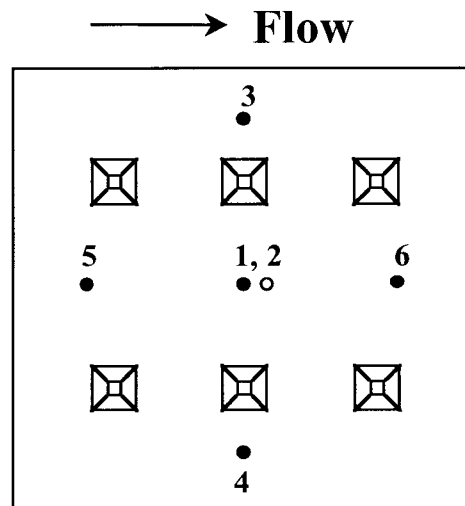


Figure 12 – Thermocouple locations for the CMC acoustic tiles. All thermocouples were attached to the hot side of the tiles, with the exception of the one labeled #2. This one was on the cold side, opposite of # 1 in the center of the tiles.

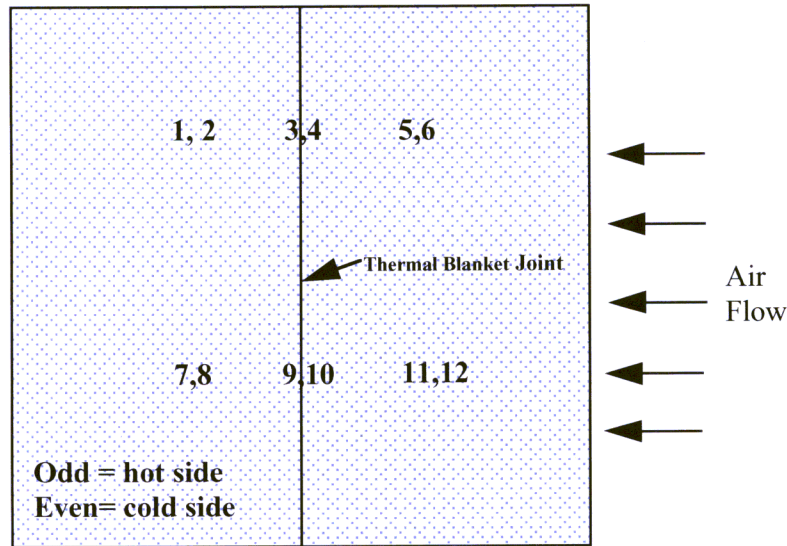


Figure 13 – Thermocouple locations for the TPS. Odd numbered thermocouples were attached to the hot side, and even numbered thermocouples were attached to the cold side of the TPS.

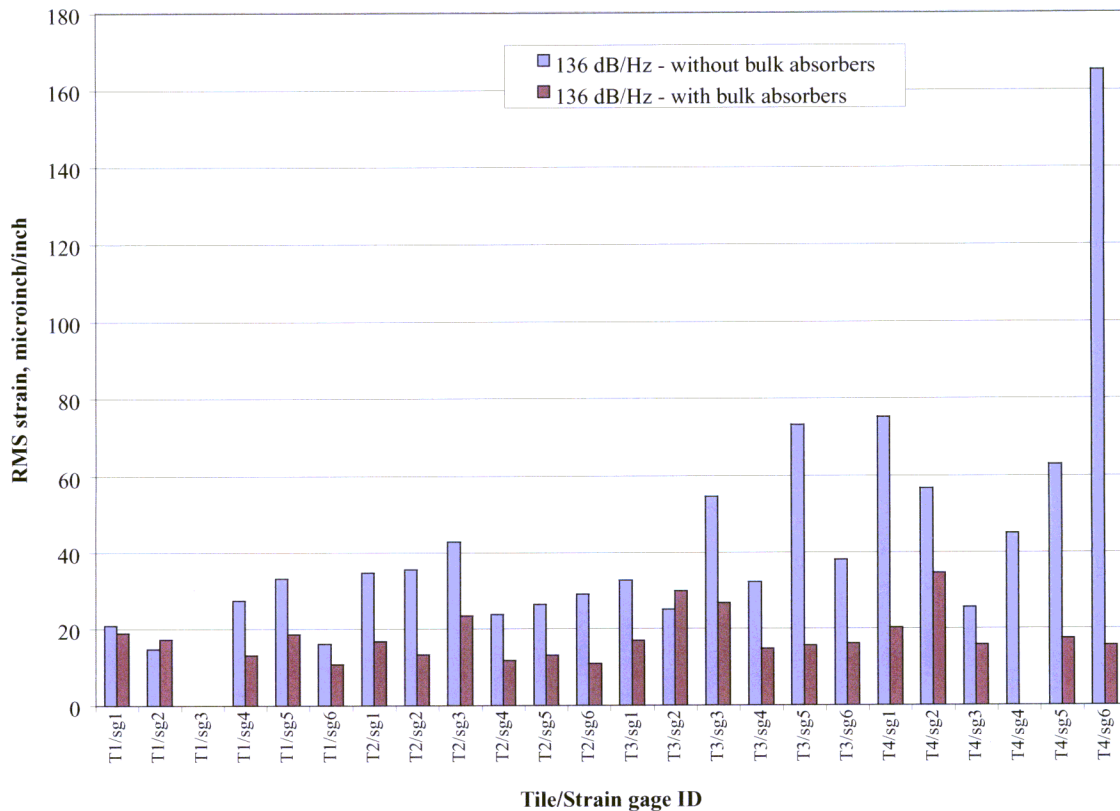


Figure 14 – RMS strains on the CMC acoustic tiles measured during exposure to 136 dB/Hz acoustic load at ambient temperature. The first two characters of the data point labels for the x-axis denote the tile number, and the rest of the characters denote the strain gage number.

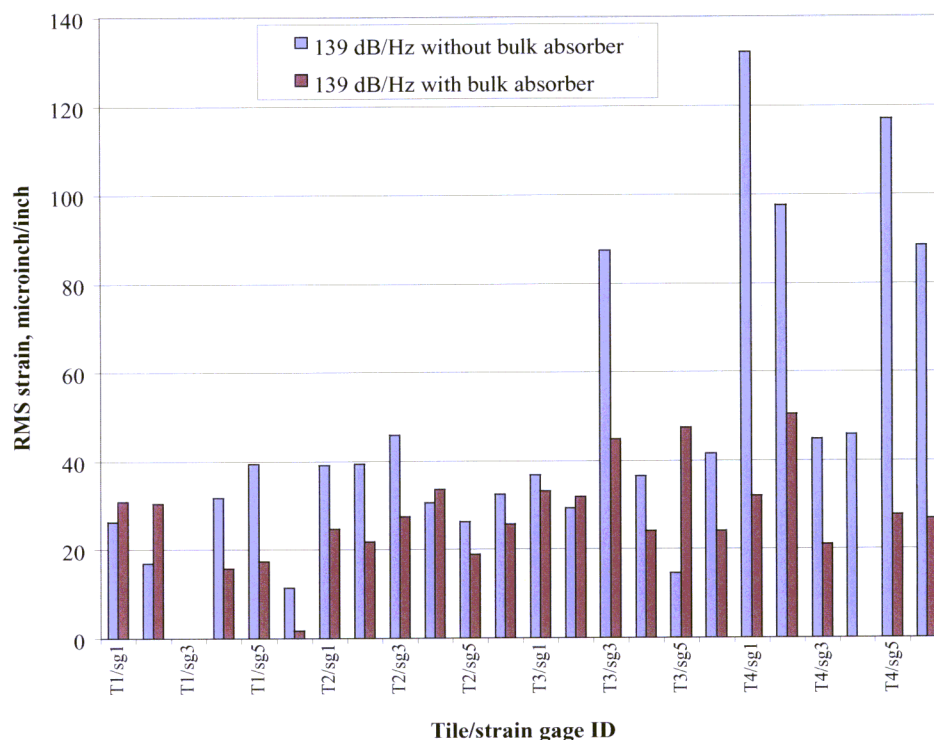


Figure 15 – RMS strains on the CMC acoustic tiles measured during exposure to 139 dB/Hz acoustic load at ambient temperature. The first two characters of the data point labels for the x-axis denote the tile number, and the rest of the characters denote the strain gage number.

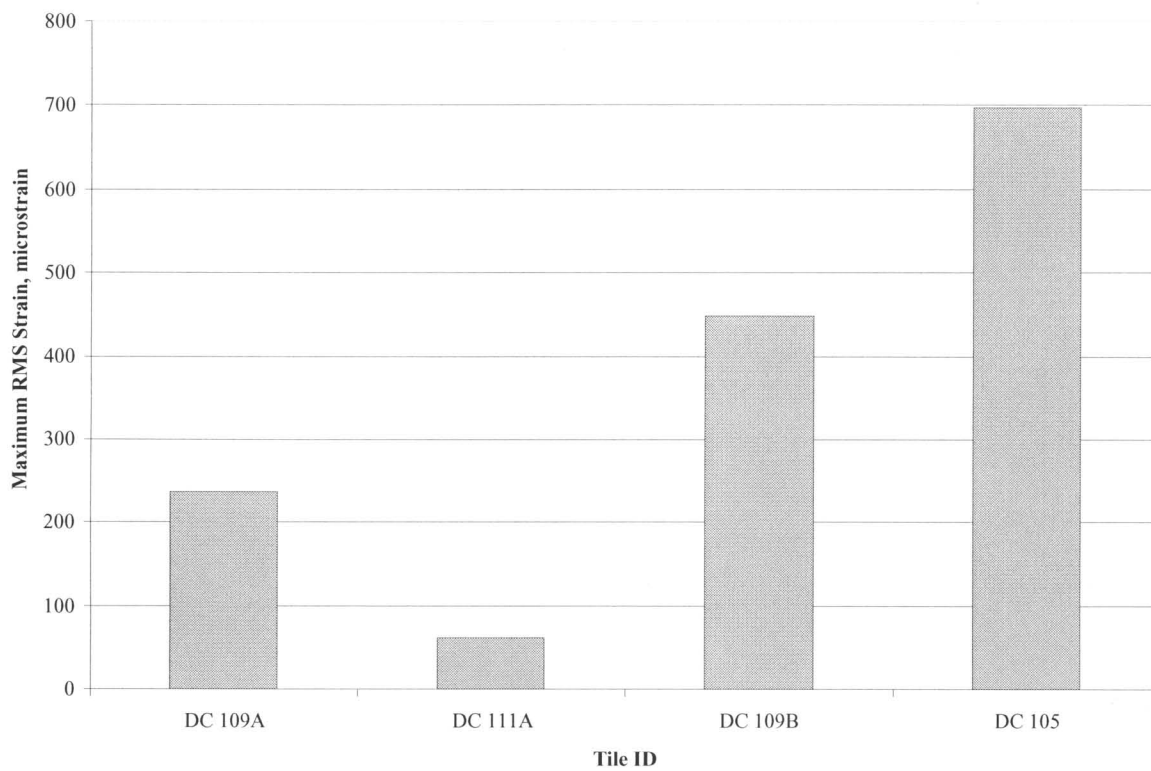


Figure 16 – Maximum strains measured in each CMC acoustic tile during ambient temperature acoustic testing.

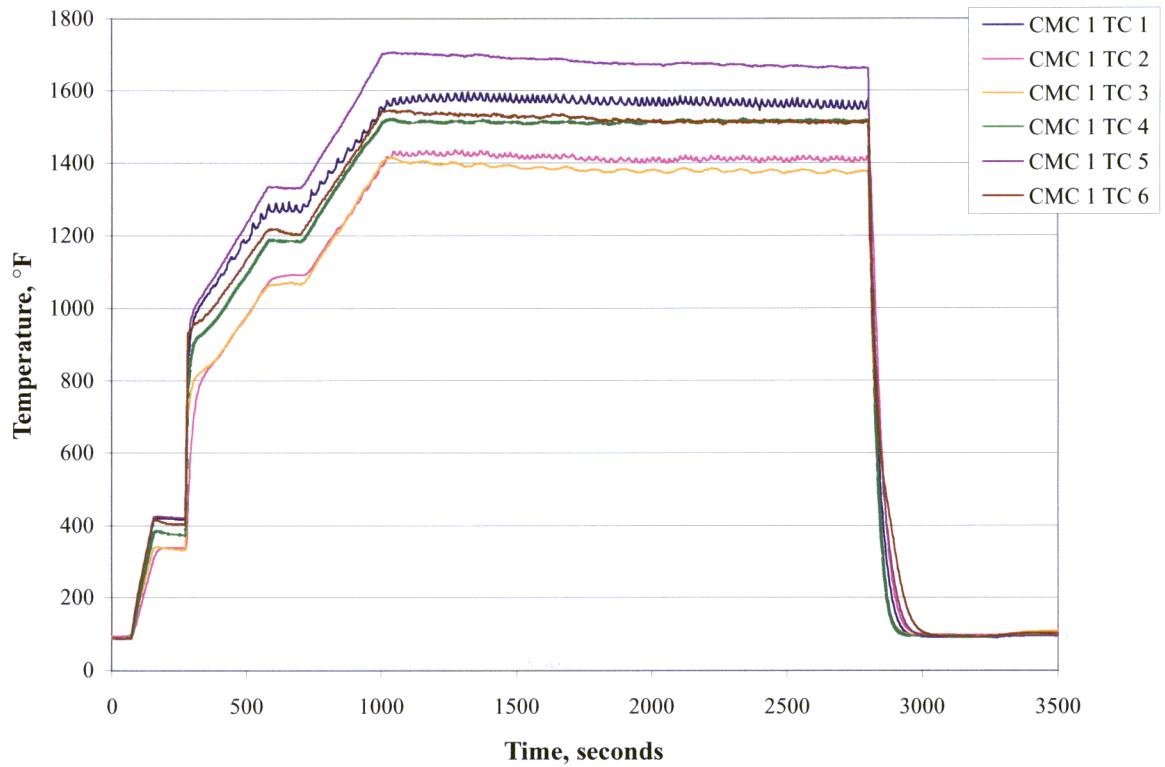


Figure 17a – Temperatures measured in CMC tile DC 109A during test cycle 1.

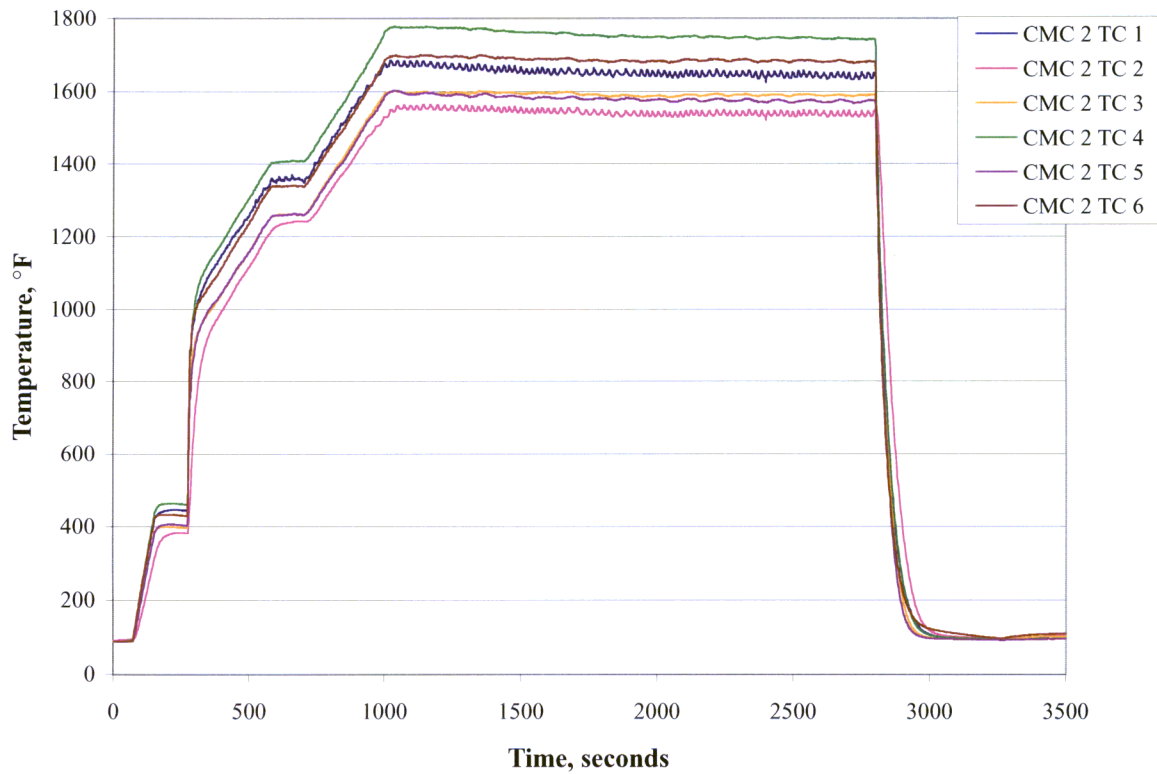


Figure 17b – Temperatures measured in CMC tile DC 111A during test cycle 1.

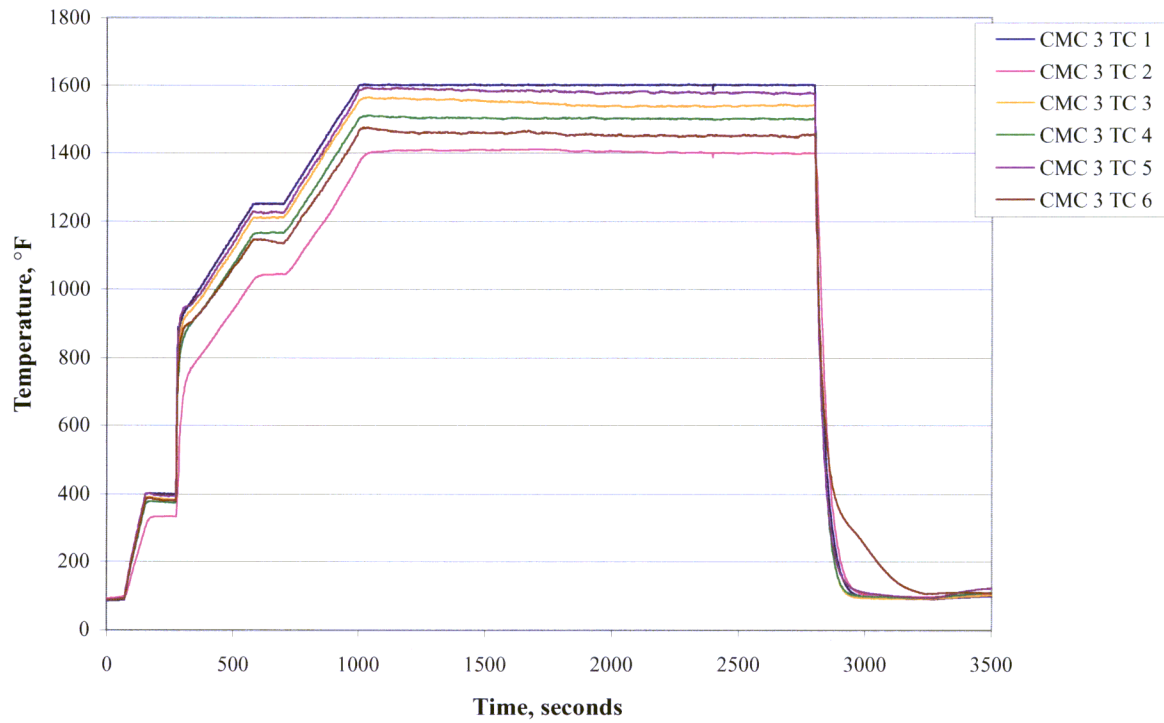


Figure 17c – Temperatures measured in CMC tile DC 109B during test cycle 1.

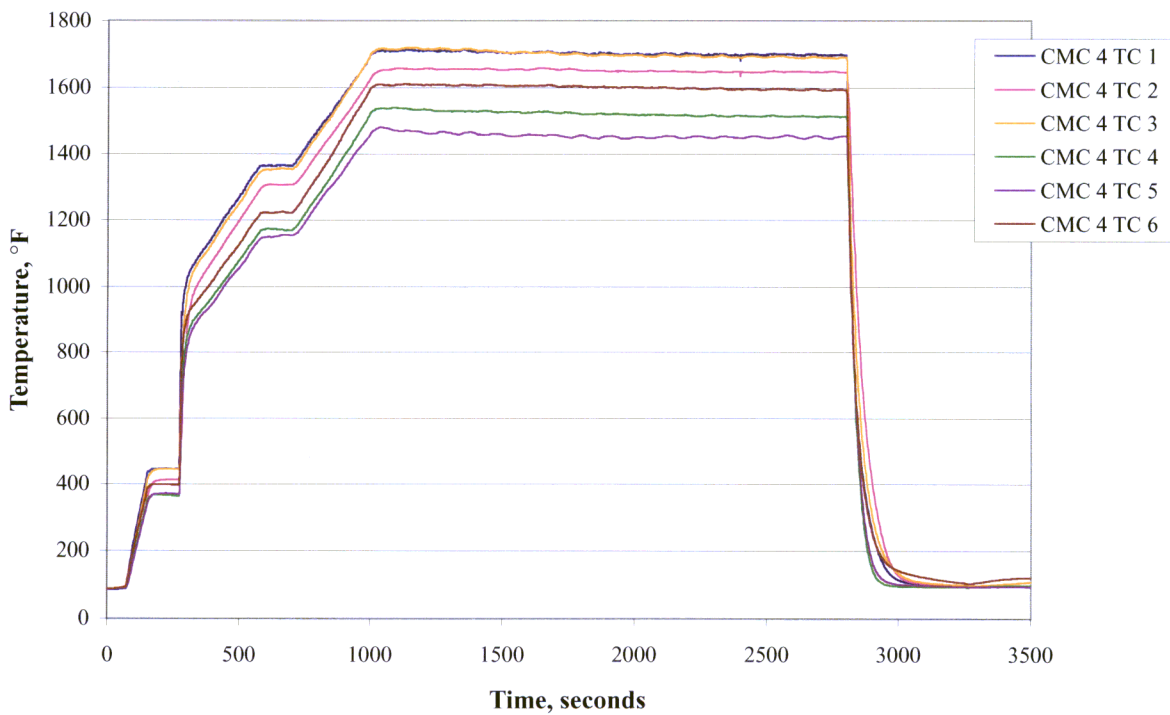


Figure 17d – Temperatures measured in CMC tile DC 105 during test cycle 1.

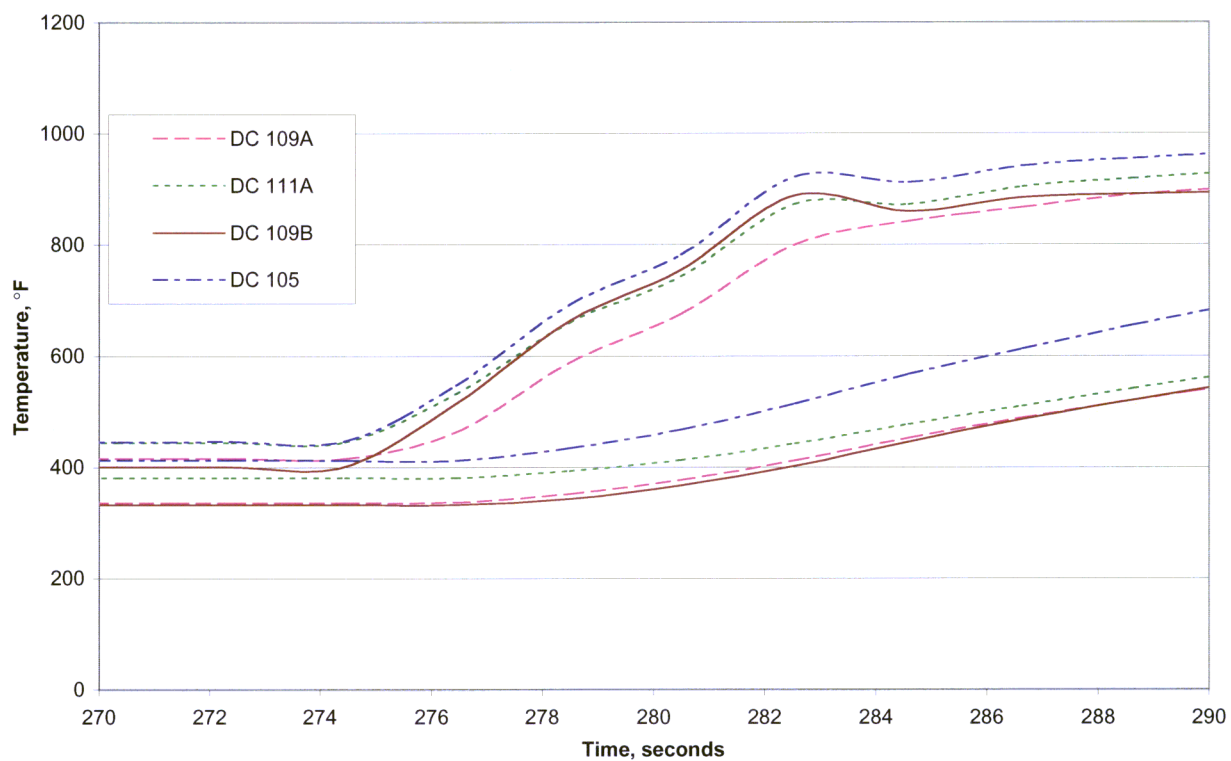


Figure 18 – Temperature versus time for the four CMC tiles during the transient heating portion of the thermal-acoustic cycle. Temperatures shown are the hot and cold sides at the middle of each CMC tile. Data is for cycle 1.



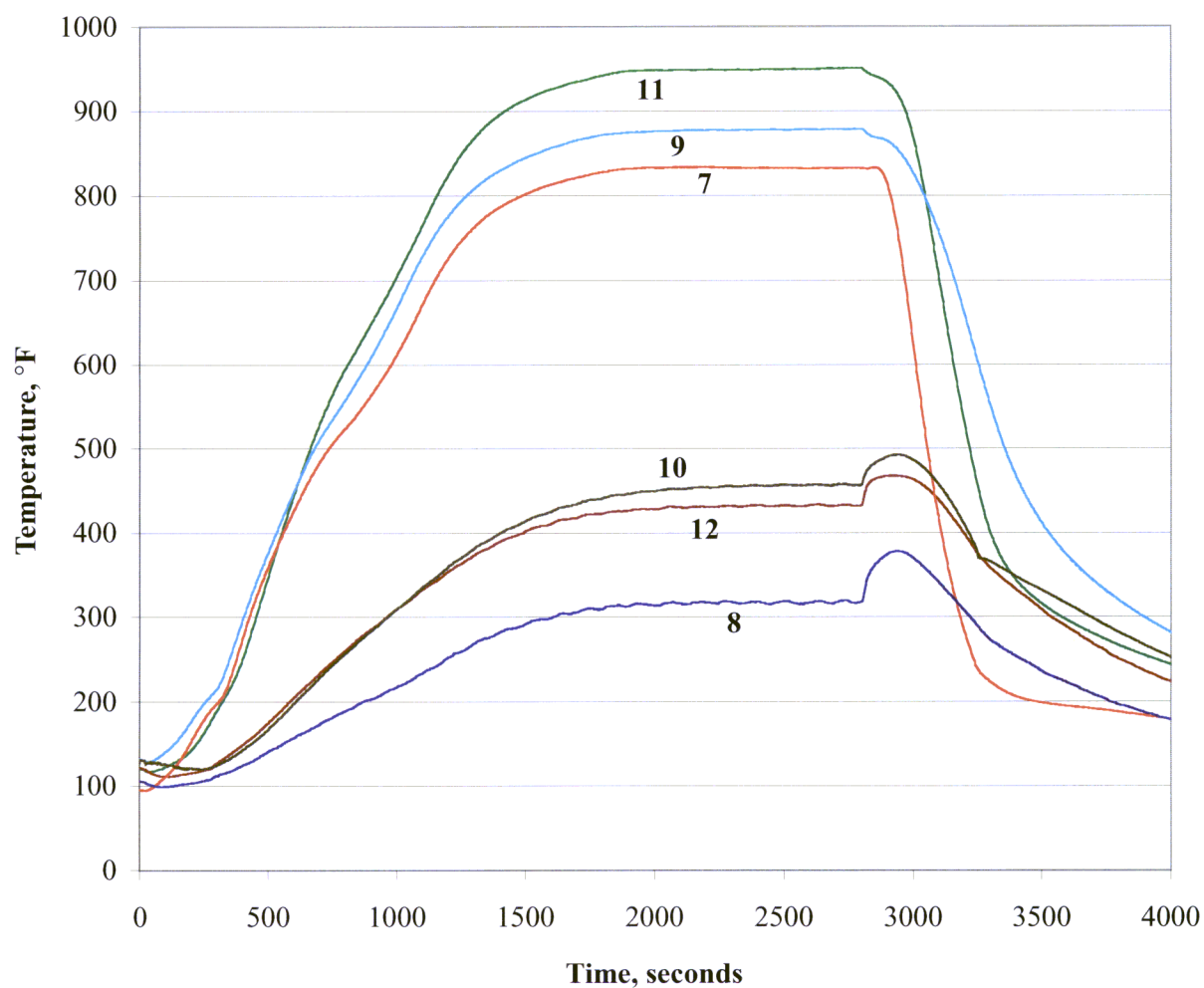


Figure 19 – Temperature versus time for the TPS under CMC tiles DC 109B and DC 105 (3 & 4). Data is for cycle 1. The curve labels are the thermocouple identification numbers shown in Figure 13.

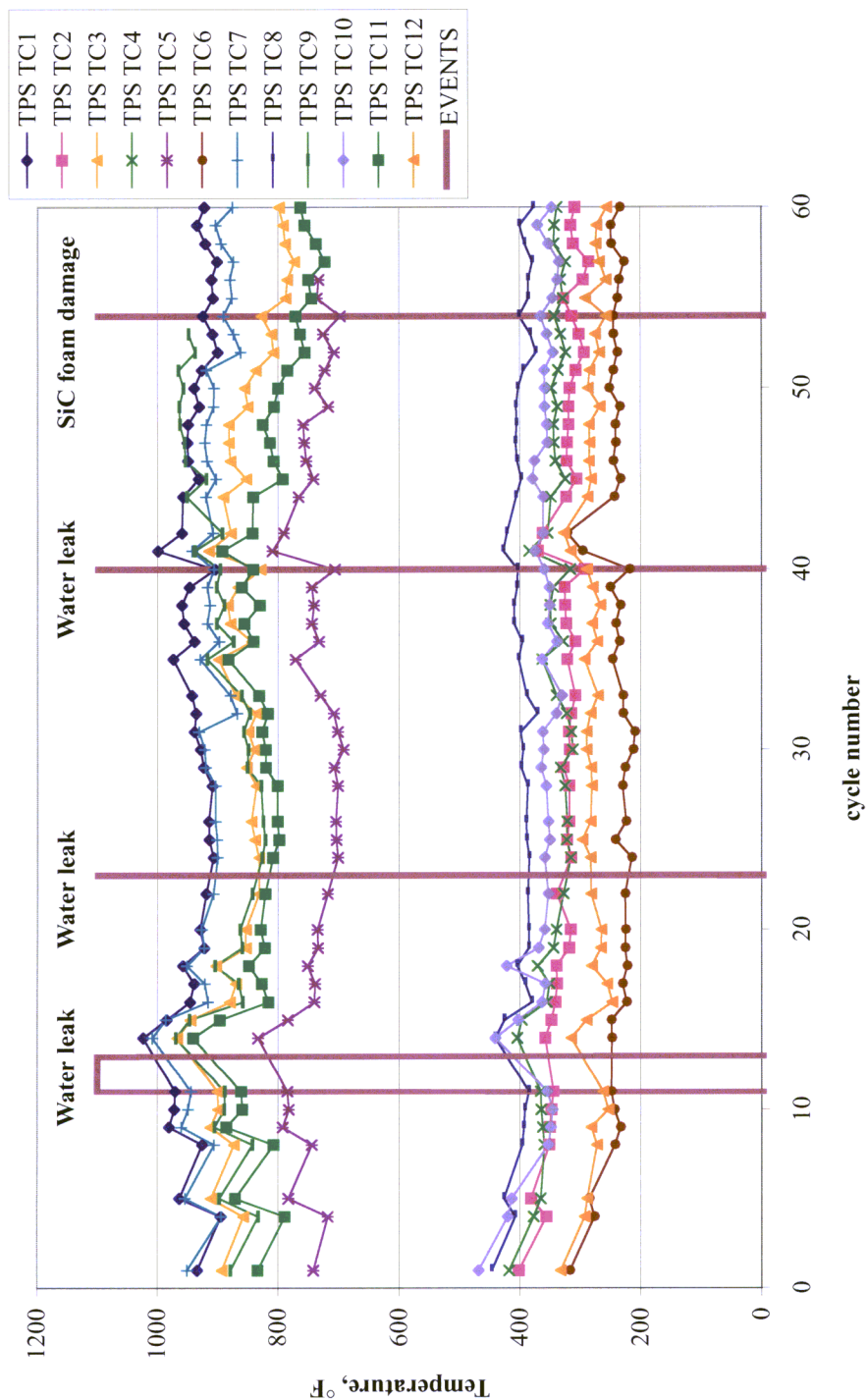


Figure 20 – Maximum and minimum temperatures for each thermocouple on the TPS as a function of cycle number.

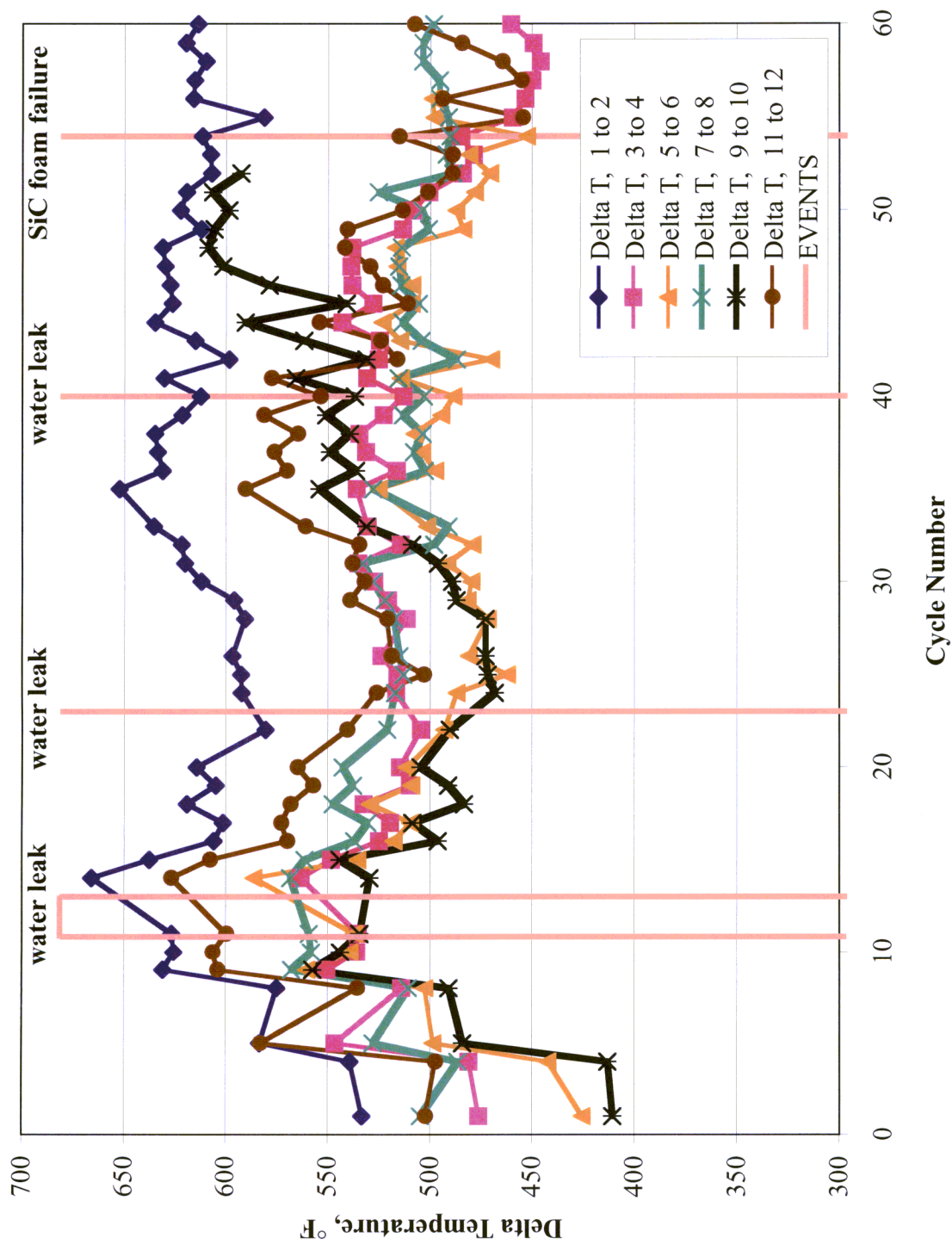
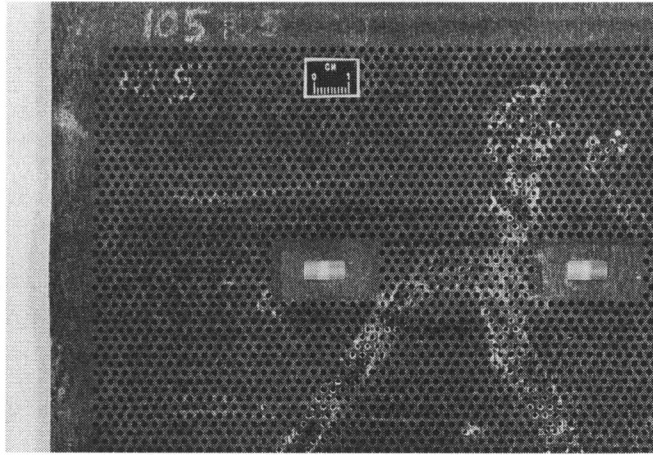


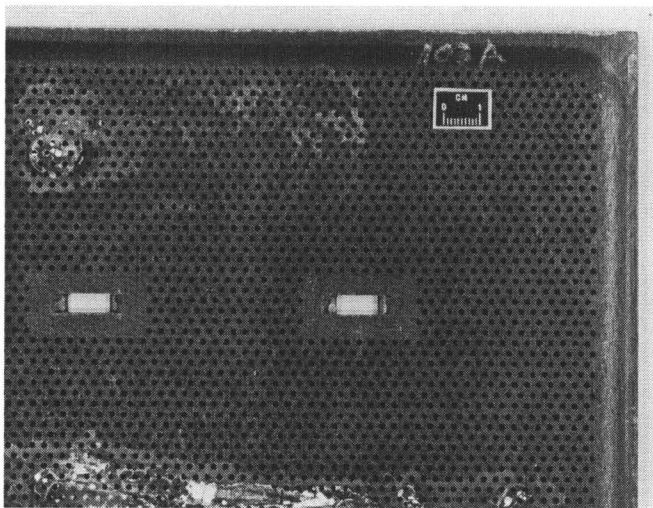
Figure 21 – Maximum through-thickness delta T for the TPS as a function of cycle number.



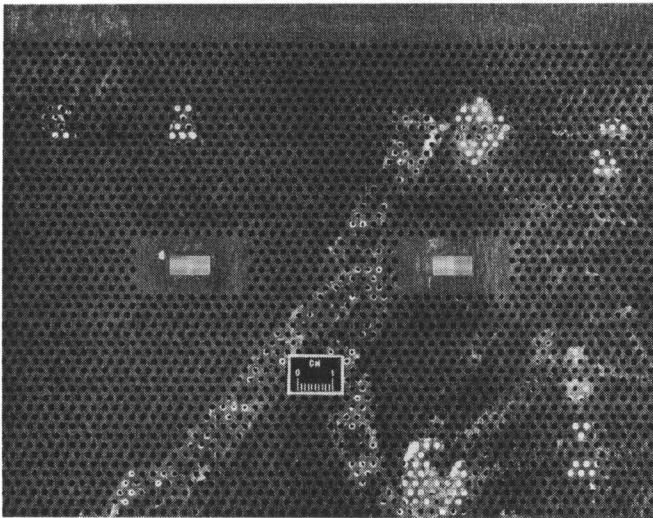
Figure 22 – Photograph of the CMC acoustic tiles after completion of the durability test.



a)



b)



c)

Figure 23 – Views of the CMC tiles after the durability test; a) cold side of tile 105, b) hot side of tile 103A, and c) cold side of tile 109A.

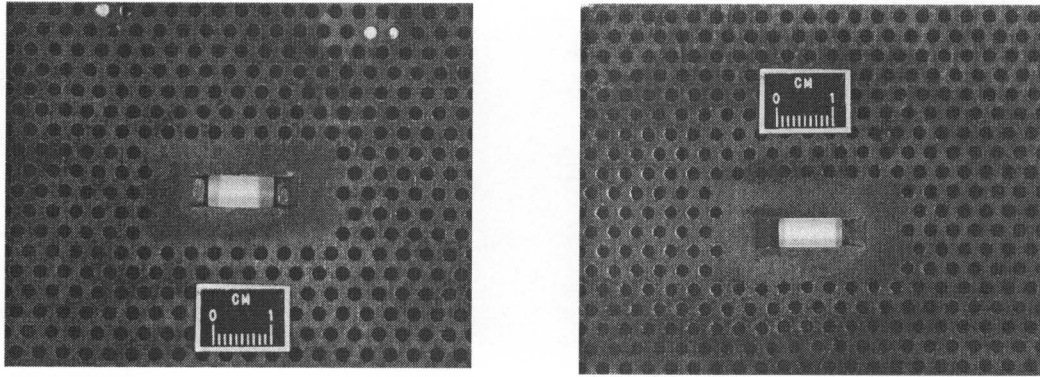


Figure 24 – Fastener holes in tile 111A after completion of the durability test; a) hole that held a fastener, with slight discoloration, b) hole that was not used during the test.

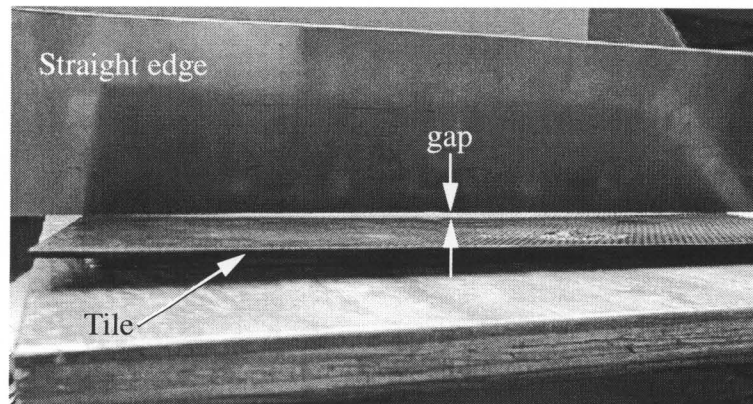


Figure 25 – Edge-on view of CMC tile DC 105, showing the out-of-plane warpage that occurred during the durability test.



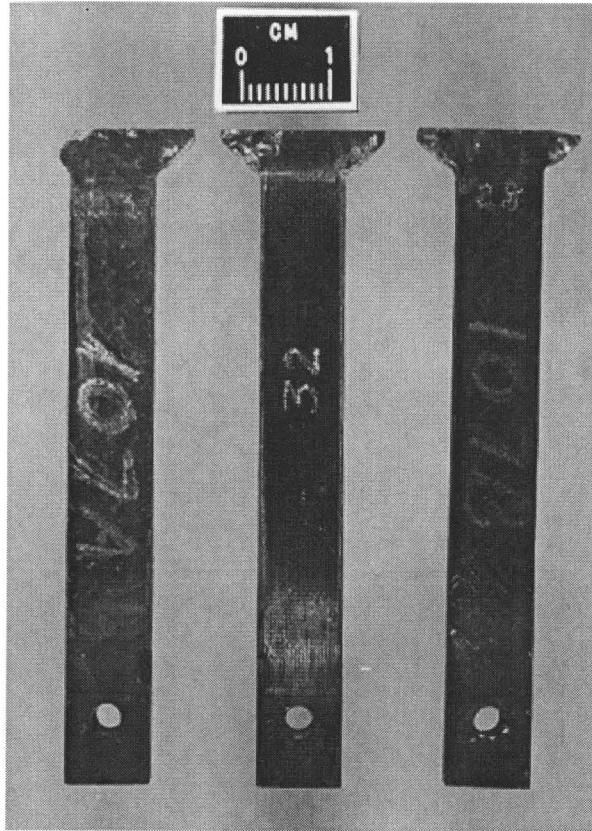


Figure 26 – Typical damage observed in the CMC fasteners.

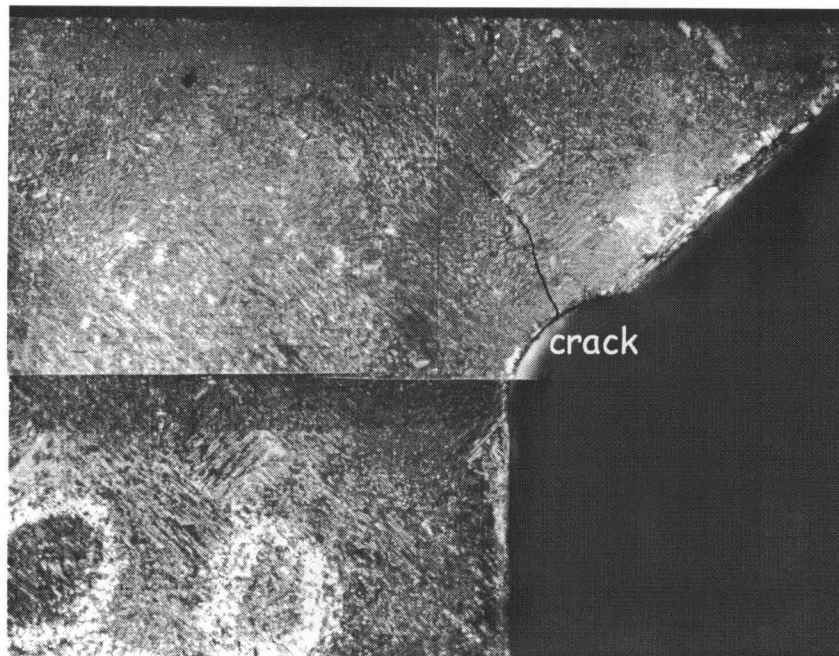


Figure 27 – Photograph of fastener #20, showing a crack in the head of the fastener.

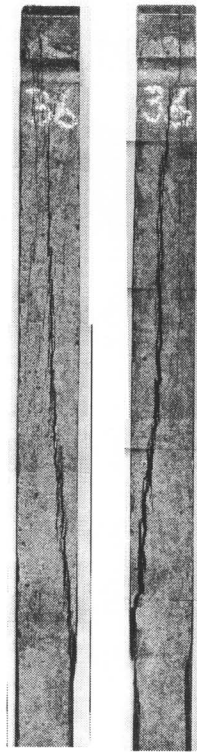
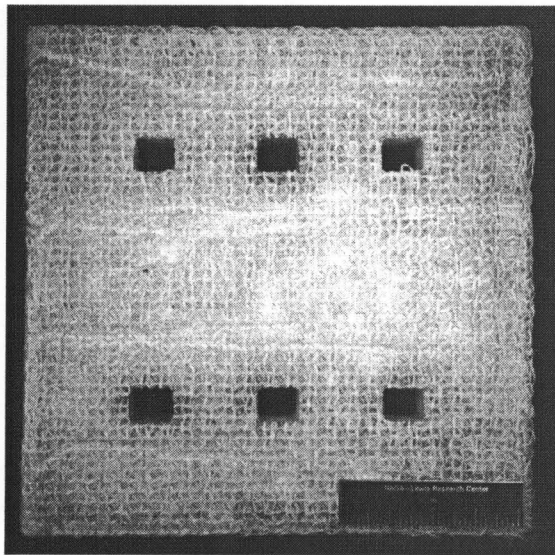
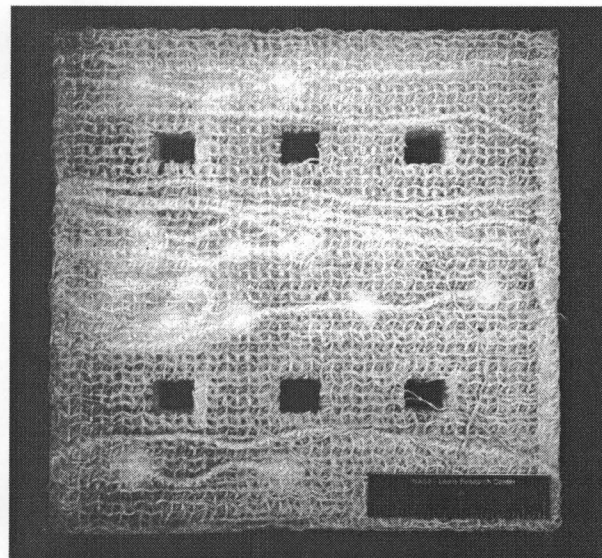


Figure 28 – Interlaminar damage in a CMC fastener, viewed by photographs of both edges of the fastener.

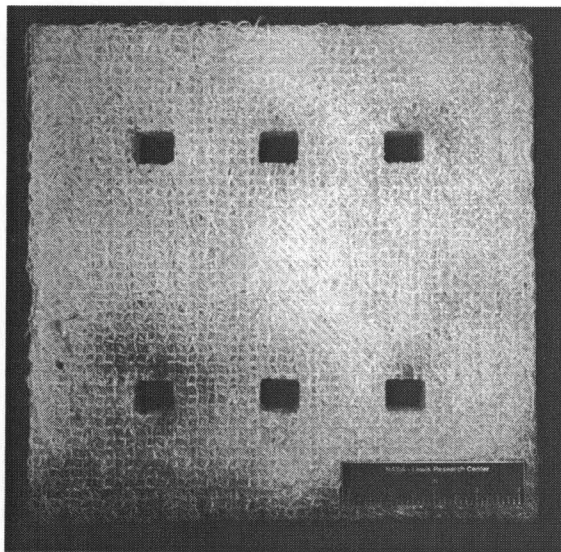




a)



b)

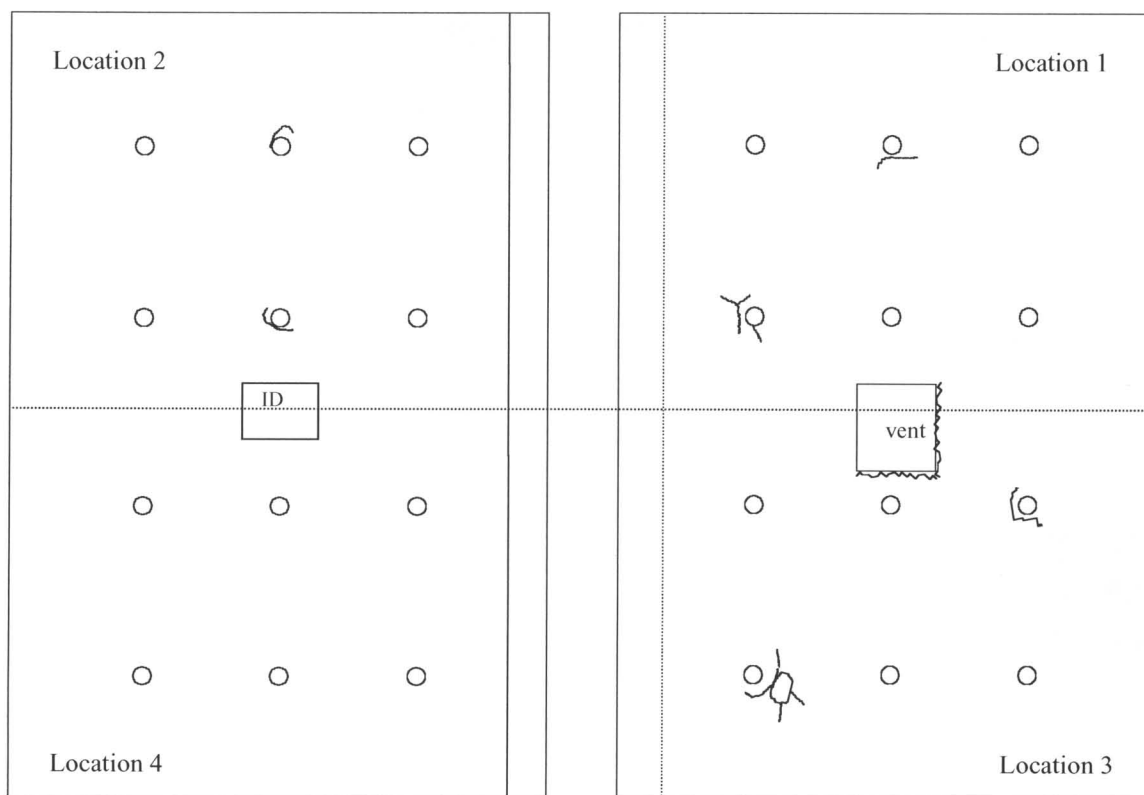


c)



d)

Figure 29 – Post-test view of acoustic absorber panels; a) hot side of T-foam panel 1973-26, b) hot side of T-foam panel 1973-41, c) cold side of T-foam panel 1973-30, d) cold side of Ultramet SiC foam.



Serial Number 2

Serial Number 1

Figure 30 – Schematic of cracking on the hot side of the TPS panels after the hot acoustic durability test.

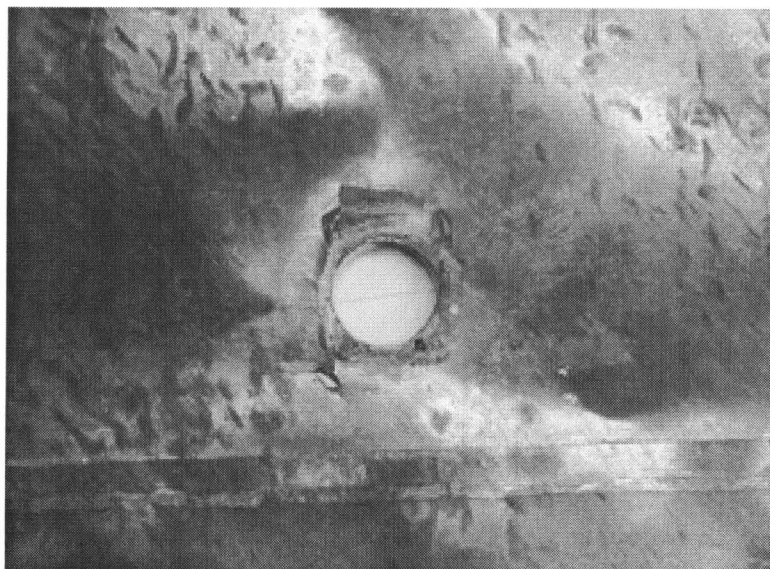


Figure 31 – Cracking observed in the TPS after the hot acoustic durability test.



Figure 32 – Imprint of a  $\text{Si}_3\text{N}_4$  spacer on the hot side foil of the TPS subjected to the durability test.

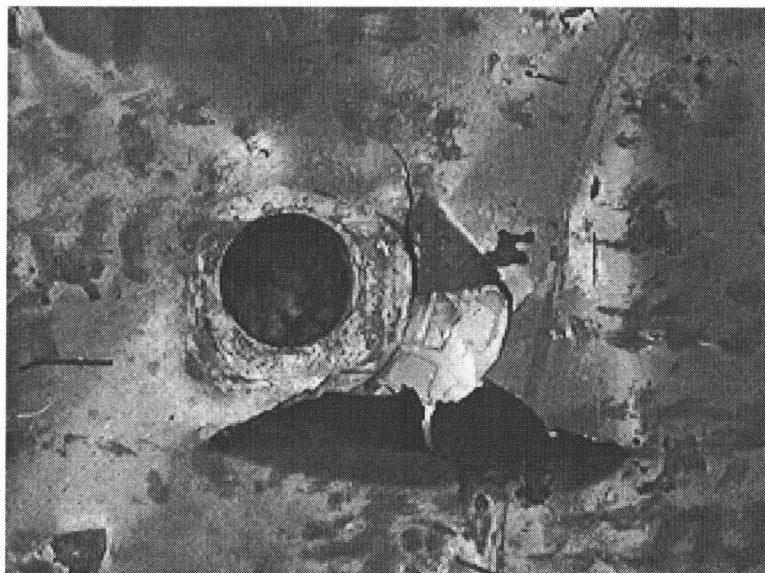


Figure 33 – Damage of TPS serial number 1 in the region that was under the Ultramet SiC foam.

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1. REPORT DATE (DD-MM-YYYY) 01-03-2008		2. REPORT TYPE Technical Memorandum		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE Post Test Evaluation of HSCT Nozzle Acoustic Liner Subcomponents Subjected to a Hot Acoustic Durability Test				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Verrilli, Michael, J.; Lee, Kuan				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER WBS 984754.02.07.03.11.03	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration John H. Glenn Research Center at Lewis Field Cleveland, Ohio 44135-3191				8. PERFORMING ORGANIZATION REPORT NUMBER E-16184	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001				10. SPONSORING/MONITORS ACRONYM(S) NASA	
				11. SPONSORING/MONITORING REPORT NUMBER NASA/TM-2008-215015	
12. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified-Unlimited Subject Categories: 04 and 07 Available electronically at <a href="http://gltrs.grc.nasa.gov">http://gltrs.grc.nasa.gov</a> This publication is available from the NASA Center for Aerospace Information, 301-621-0390					
13. SUPPLEMENTARY NOTES This research was originally published internally as HSR075 in June 2000.					
14. ABSTRACT The acoustic liner system designed for use in the High Speed Civil Transport (HSCT) was tested in a thermal-acoustic environment. Five ceramic matrix composite (CMC) acoustic tile configurations, five bulk acoustic absorbers, and one thermal protection system design were tested. The CMC acoustic tiles were subjected to two 2 3/4 hr ambient temperature acoustic exposures to measure their dynamic response. One exposure was conducted on the tiles alone and the second exposure included the tiles and the T-foam bulk absorber. The measured tile RMS strains were small. With or without the T-foam absorber, the dynamic strains were below strain levels that would cause damage during fatigue loading. After the ambient exposure, a 75-hr durability test of the entire acoustic liner system was conducted using a thermal-acoustic cycle that approximated the anticipated service cycle. Acoustic loads up to 139 dB/Hz and temperatures up to 1670 °F (910 °C) were employed during this 60 cycle test. During the durability test, the CMC tiles were exposed to temperatures up to 1780 °F and a transient through thickness gradient up to 490 °F. The TPS peak temperatures on the hot side of the panels ranged from 750 to 1000 °F during the 60 cycles. The through thickness delta T ranged from 450 to 650 °F, varying with TPS location and cycle number. No damage, such as cracks or chipping, was observed in the CMC tiles after completion of the testing. However, on tile warped during the durability test and was replaced after 43 or 60 cycles. No externally observed damage was found in this tile. No failure of the CMC fasteners occurred, but damage was observed. Cracks and missing material occurred, only in the fastener head region. No indication of damage was observed in the T-foam acoustic absorbers. The SiC foam acoustic absorber experienced damage after about 43 cycles. Cracking in the TPS occurred around the attachment holes and under a vent. In spite of the development of damage, the TPS maintained its insulative capability throughout the durability test. The durability test results demonstrate damage-tolerant CMC tile, CMC fastener, TPS, and T-foam absorber designs for the combined thermal and acoustic engine nozzle environment.					
15. SUBJECT TERMS HSCT; CMC; Nozzle; Acoustic liner					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES 49	19a. NAME OF RESPONSIBLE PERSON STI Help Desk (email: <a href="mailto:help@sti.nasa.gov">help@sti.nasa.gov</a> )
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U			19b. TELEPHONE NUMBER (include area code) 301-621-0390



